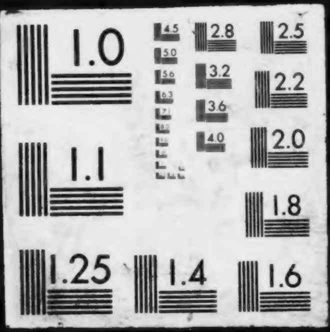
1 OF 2

PB

253 675


1.0
4.5
5.0
5.6
6.3
2.8
3.2
3.6
4.0
2.5
2.2
2.0
1.8
1.1
1.25
1.4
1.6

U.S. DEPARTMENT OF COMMERCE
National Technical Information Service

PB-253 675

TRANSPORT OF DIGESTED SLUDGE SLURRIES FOR ECONOMIC DISPOSAL

MASS TRANSPORT BY PIPELINE TO DISPOSAL OR TO USE FOR STRIP MINE RECLAMATION

RAND DEVELOPMENT CORPORATION

PREPARED FOR
FEDERAL WATER POLLUTION CONTROL ADMINISTRATION

15 NOVEMBER 1966

173092

PB 253 675

TRANSPORT OF DIGESTED SLUDGE SLURRIES
FOR ECONOMIC DISPOSAL

Mass Transport by Pipeline to Disposal or to Use for Strip Mine Reclamation

Prepared for:

Federal Water Pollution Control Administration
U. S. Department of the Interior
Washington, D.C.

Contract No. PH 86-65-21

Bertram C. Raynes
Vice President for
Applied Research
Rand Development Corp.
Cleveland, Ohio

November 15, 1966

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U. S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

TABLE OF CONTENTS

Page

I. ABSTRACT 1

II. INTRODUCTION 5

Fig. 1 - Filtration & Incineration Costs 7
Table I - Disposal by Filtration & Incineration 9
Fig. 2 - Average Pipeline Transport Costs 10
Fig. 3 - Pipe Sizes for Transport of Sludge at 5% Solids 13

III. DISCUSSION 14

A. Fluid Flow of Sludge Slurries 15

Fig. 4 - Influence of Solids Concentration in Sludge Slurries Upon Minimum Velocities at Which Fully Turbulent Flow is Achieved. Friction Head Loss is Shown, and the Region of Velocities in Which Fluids are Generally Economically Transported is Indicated. 18

B. Flow Character of Plastic Materials in Pipes 19

Fig. 5 - Flow of Newtonian Type Materials 22

C. Sludge Slurry Flow Characteristics 24

Table II - Water Turbulent Flow 25
Table III - Calculated Minimum Velocity for Complete Turbulence for Sludges in a Range of Pipe Sizes and Suspended Solids Concentrations 27

D. Simple Hydrometer Determination of Slurry Type 28

Fig. 6 - Flow of Plastic Sludges 29
Fig. 7 - Graph of Specific Gravity (Hydrometer) and Solids Concentration of Newtonian and Plastic Ranges Sludge 31

E. Pumping Test Work & Apparatus 32

Fig. 8 - Simplified Diagram of Pumping Study Test Apparatus 35
Fig. 9 - Friction Head Loss at Velocities of 1 Foot to 4 Feet Per Second in 2-Inch Diameter Pipe for Sludge from 2 to 13% Solids Concentration 37
Fig. 10 - Friction Head Loss at Velocities of 1 Foot to 4 Feet Per Second in 1-1/2-Inch Diameter Pipe for Sludge from 2 to 12% Solids Concentration 38

F. Testing Procedure 39

Continued . . . .

TABLE OF CONTENTS (Cont'd.)

Page

Fig. 11 - Overall View of Sludge Pumping Test Apparatus 41
Fig. 12 - Close-Up View of Sludge Pumping Test Apparatus 42

IV. RECLAMATION 44

Use of Sludge Slurries 44

Table IV - Terminal Facility & Operation Costs 45
Table V - pH of Sludge, Sludged Spoil & Untreated Spoil 48

V. APPENDICES

A. Data Used in the Construction of Graphs 9 and 10 53

B. Basic Data Used for the Computation of Values in Appendix A. 56

C. Terminal Facility Costs 70

D. Savings 72

E. Cost Estimation 77

F. Digested Sludge Production 86

VI. REFERENCES 89

VII. ACKNOWLEDGEMENTS 95

ECONOMIC TRANSPORT OF DIGESTED SLUDGE SLURRIES

I. ABSTRACT

This document describes the development of a more economical method for the disposal of digested sludge solids produced in conventional biological sewage treatment plants. The process steps of filtration and incineration or drying are eliminated. Instead the entire sludge slurry is transported via pipelines to disposal on land which may then be at considerable distances from the treatment plant. The sludge slurry is a valuable organic plant culture and nutrient which can be advantageously used as a reclamation aid on strip mine spoil or on other denuded land areas.

This disposal concept helps in the control of the pollution of surface waters in several significant ways. First, sewage treatment plant capital and operating costs can be reduced so that increasingly more communities will be able to afford such treatment and can be induced to provide it. Second, digested sludge liquor and solids would be disposed of or used so that they would not reach surface waters.

Third, the intelligent disposal of digested sludge slurries upon devastated land areas, such as strip mine spoil areas, can restore a viable ground cover to these areas. This can help in the abatement of acid mine drainage pollution in the surface waters in the disposal areas, and also reduce pollution of surface waters by erosion.

Thus, this concept of disposal combines both economic disposal of digested sludge slurries and also reclamation. When digested sludge slurries are

transported using pipeline technology, the concept it is shown is economically justifiable from the standpoint of cost savings to municipalities alone. The other benefits of reclamation, pollution abatement, and possible future economic benefit are bonuses. For example:

> A municipality of just over two million people, treating its sewage by conventional means and producing 590,000 gallons of about 5 percent digested sludge slurry per day, it is estimated can pump its slurry a distance of 160 miles and dispose of it - without beneficial application of sludge as a restoration aid - at a cost of $6.00 per ton of dry solids. The total cost of transportation and constructive application of the sludge for land restoration purposes would be $7.25 per dry ton. This estimated cost includes interest and depreciation on capital investment; operating and maintenance costs; and utilities, labor, and supervision. Alternatively the municipality would incur an expense in the range of $35.00 per ton to vacuum dry and incinerate these sludge solids.
>
> The pipeline would be 8 inches in diameter. The velocity through the pipe of the 5 percent solids concentration slurry would be chosen to be 2.6 feet per second both to minimize solids settling and also to reduce power costs. The total working head would be in the order of 15,000 psi.
>
> The total cost of transporting and disposing of the slurry plus using it as a restoration aid would be $7.25 per dry ton.
>
> A municipality of 200,000 people, treating its sewage by conventional means and producing some 33,000 gallons of about 8 percent digested sludge slurry per day can pump its slurry a distance of 40 miles and dispose of it at a cost of $7.00 per dry ton of solids. Alternatively the municipality would incur an expense of approximately $60.00 per ton to vacuum dry and incinerate the sludge solids.
>
> The pipeline would be 2-1/2 inches in diameter. The velocity of the slurry through the pipe, diluted to 4 percent solids concentration, would be chosen to be 3.0 feet per second both to minimize solids settling and also to reduce power costs. The total working head would be in the order of 2500 psi.
>
> The total cost of transporting plus disposing of the slurry as a restoration aid would be $10.50 per dry ton.

At the terminus of the pipeline the slurry would be used as an organic plant nutrient by being spread or otherwise disposed of on land prepared only to the extent that surface run-off is prevented. If reclamation is intended, seeds of suitable plants will be introduced into the sludge. Estimated costs of this operation are given. For the municipality of two million persons, the cost will be $70.00 per acre or $1.25 per dry ton.

In the work conducted to demonstrate the economics of piping digested sludge slurries and their use to restore strip mine lands, a number of obvious and some more subtle factors were examined. Some relate directly to the nature of the material being transported. Special consideration of the fluid nature of digested sludge slurries was given, and described herein; these include especially the fluid flow characteristics and practical pumping velocities desirable to reduce plugging and maintenance problems. Less obvious factors include such matters as volume of material to be transported; the length of the line; pipe diameter; materials of construction; financing; service factor; and so on.

It is not the purpose of this document to attempt an exhaustive analysis of all of the pertinent factors. This report recommends velocities of transport for digested sludge slurries, the preferred slurry concentration for transport, and indicates economic pipe diameters. The appendix provides certain additional information, including a selection of graphs and curves developed during the work. Using this report, sewage treatment plant operators and municipality officials can make preliminary cost estimates of the savings made available through the use of the concept of disposing of digested sludge slurries through pipelines to distance disposal areas.

The design of a pipeline is a cost optimization problem. A large number of practical and engineering parameters exist, including such obvious ones as length of the line; volumes of material to be transported; terrain and choice of right of way; pipe diameter, material, and wall thickness; and so on. Less obvious factors include such matters as financing; service factor; operating conditions; and pumping velocities. This report covers the most significant of these factors.

The pumping and hydrometer work to be discussed later, indicate the economic pipe diameter, the recommended velocity of transport for slurry, and the preferred slurry concentration for transport. Using these results and the earlier report curves, it is a simple matter to make preliminary estimates of the cost of transport. The cost of disposal or of land restoration once the slurry is delivered to a selected area has also been estimated and can simply be added to the estimated transport costs.

II. INTRODUCTION

Digested sludge slurries are formed in conventional sewage treatment plants. The handling and disposal of sludge solids account for about half of the overall cost of sewage treatment, particularly in those plants which use vacuum filtration and incineration steps.

A less expensive conventional method of sludge disposal is the sludge drying bed. That practice, although still widely used, has fallen into some disgrace for numerous reasons: the cost of land directly adjacent to and generally considered available for treatment plants is considered excessive; the fertilizer values of the sludge solids are ordinarily insufficient in comparison to commercial nitrogen-phosphate fertilizers to warrant drying and truck haulage for even short distances; and the continuing use of a single limited disposal area ultimately returns organic plant nutrients to surface waters and possibly to ground water.

The Federal Water Pollution Control Administration, U. S. Department of the Interior, is sponsoring work to bring to use more economic and practical means for disposal and beneficial use of digested sludge slurries. The work is being carried out by Rand Development Corporation; this report summarizes the pre-pilot plant efforts, involving desk studies, laboratory, field work, and pipeline testing in two small diameter pipe sizes. These actual pumping studies using sludge from conventional treatment plants have shown critically important pipeline design criteria and desirable but wide limits to sludge slurry specifications for transport purposes.

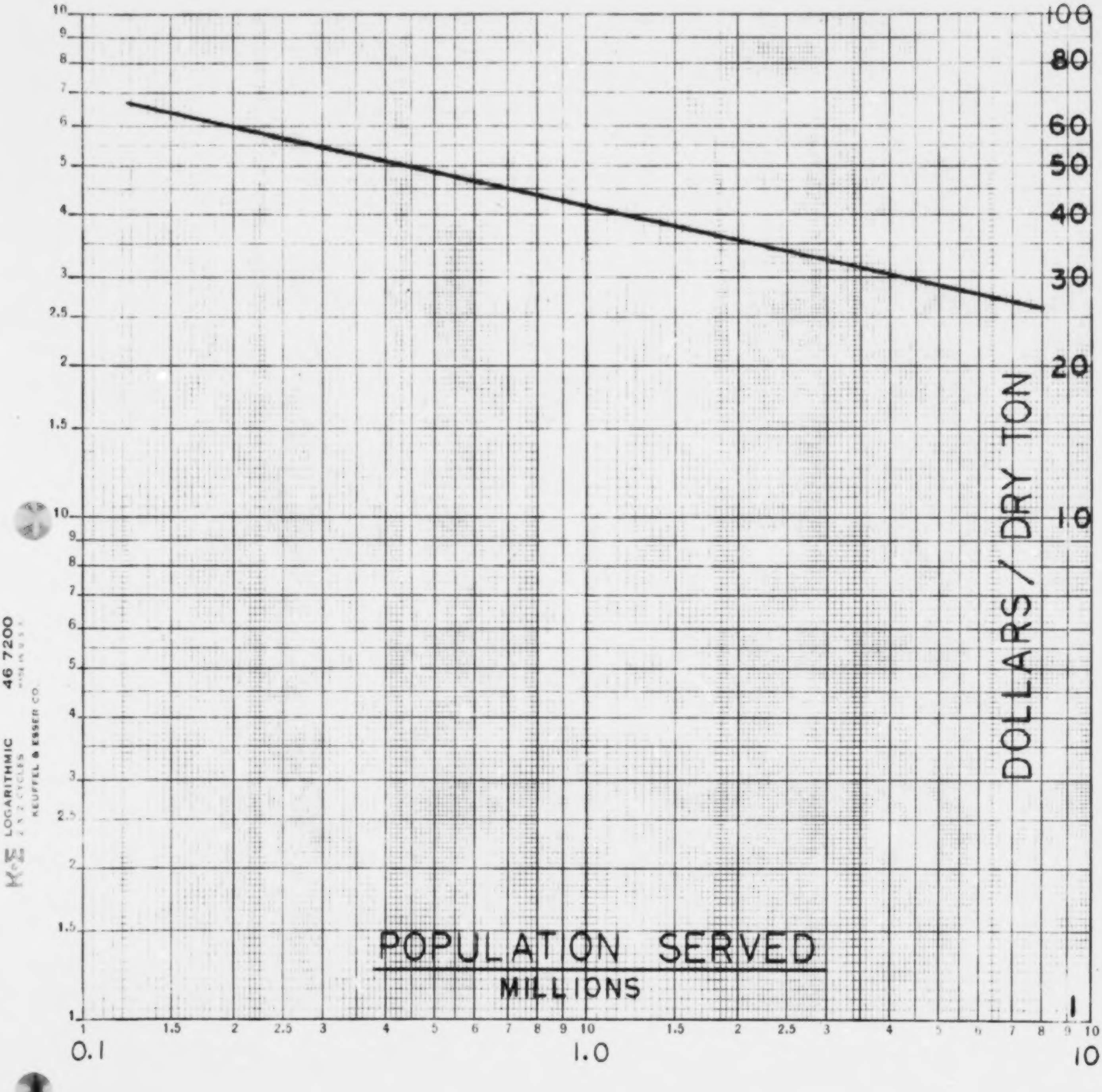
The concept being brought to the practical stage is the mass transport of digested sludge slurries by pipelining with disposal and use of the slurry as an agent in the restoration of barren areas such as strip mines. Both aspects of the procedure were previously described or well known; but this innovation incorporates two individual ideas into this new, economic procedure. Emphasis is placed upon costs savings in sewage treatment practice and especially upon the experimental data needed to design and operate economic lines for sludge slurries.

A careful evaluation by Rand Development had previously shown(1) that pipeline transport of digested sludge slurries can be expected to provide substantial savings in the cost of conventional sewage treatment. Savings become available both in operational costs and also in sewage treatment plant capital costs. A variety of conventional treatment steps are eliminated when the entire sludge slurry produced is transported as such. The disposal and restoration area may be many miles from the sewage treatment plant, and available at little or no cost. Surface water contamination can be reduced at sewage treatment plant outfalls when the slurry is pumped to a disposal area. Another water pollution control benefit is realized as top soil is generated on stripped areas, in turn reducing surface water contamination by minerals and sediments coming from these areas.

As the technology of pipelines grows, so also does the popularity. Their popularity results from the established fact that pipeline transport, when feasible, is the least expensive transport mode except perhaps barging where very long distance transport is required. Pipeline transport per

FIG. 1

FILTRATION AND INCINERATION COSTS



11/66

mile costs are low and almost constant regardless of transport distance (whereas truck, rail, and barge costs increase rapidly for short distance haulage). Pipelines can be controlled automatically, and for this and other reasons have low manpower requirements. Capital costs of pipelines of given diameters have decreased as experience has been gained in installation and operation (2-28).

The present work covers several important aspects: a prediction of possible sewage treatment cost savings when digested sludge slurry is pumped satisfactorily in relatively small diameter lines; demonstrations of pumpability of sludge slurries in such small lines; determination of the design factors involved in the transport of sludge slurries in pipes and a determination of the economic ranges of solids concentration and flow velocities; and demonstrations of the use of sludge in the restoration of strip mine areas without nuisance or undue hazard. It has been concluded, and will be shown in this report, that the economic and other aspects of pipeline transport of slurries are extremely favorable.

From the limited available published data (25, 29-33), an idea of the costs per dry ton for vacuum filtration and incineration of sludge slurries can be obtained. These costs, including capital costs, operating and maintenance expense and administrative overheads, are shown in Figure 1. The costs are shown as a single line for convenience whereas a wide variation actually is reported. See Table I.

TABLE I

Disposal by Filtration & Incineration

Population Served	$/Ton (Dry Digested Activated Sludge)
100,000	$ 60-90
500,000	50-75
1,000,000	30-50
2,000,000	25-40

Figure 2 shows estimated costs per dry ton of transporting digested sludge slurry from given distances and for various populations. These costs are taken from previous Rand Development estimates(1). In addition to showing the cost per mile rate decrease with increasing population served - that is, size of treatment plant - the influence of transport distance is also shown.

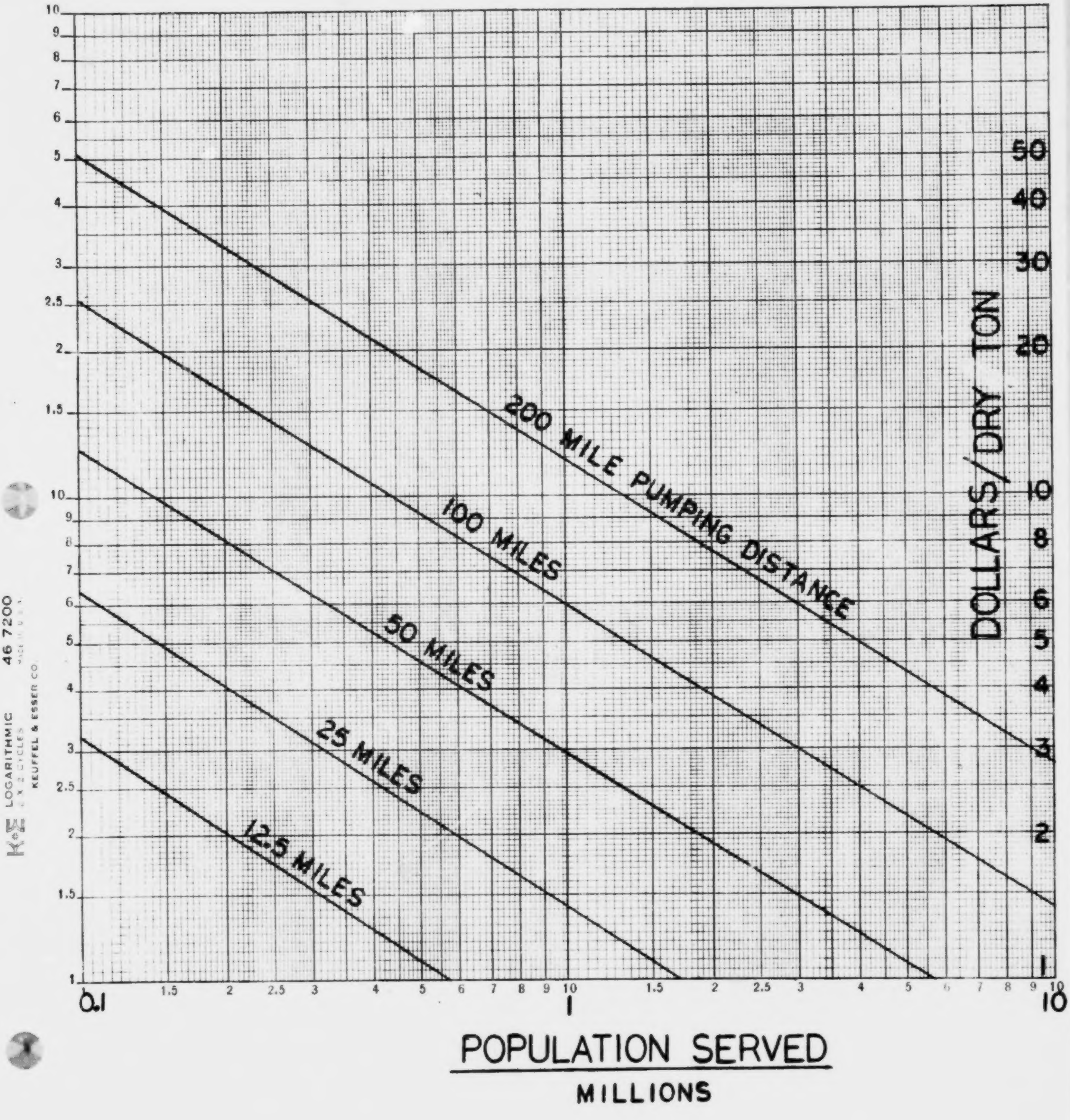
Using Figures 1 and 2 it can be seen, for example, that the average costs of vacuum filtration and incineration in a plant serving one million population equivalent is about $42 per ton dry sludge solids. By comparison, transporting the sludge slurry 100 miles would incur an average cost of only $6 per ton dry sludge solids. In such a sewage treatment plant, yearly savings of some $600,000 to $700,000 could be realized, excluding disposal or restoration costs of under $3 per dry ton on the handling of some 20,000 tons of sludge solids (dry).

What Influences Costs of Pipelining?

Pipelines in general have inherent transport cost advantages over other means (34). For example, operating manpower requirements are low, service lives are long and over-capacity need not be a large cost factor.

FIG. 2

AVERAGE PIPELINE TRANSPORT COSTS



The pipeline design must take into account the utilization or use factor. Capital costs of a sludge slurry pipeline will constitute about 80 percent of the total pipeline costs(1). If the line is so large that there is only enough sludge slurry to fill the line for one quarter of the time, at the design flow rate or velocity, the capital cost required would be about doubled, since its diameter would be twice as large. Provision for a use factor of 90 percent or more can be made economically at the head-end of the line, by providing partial intermediate feed storage where necessary. This head-end design factor is significant for small capacity sewage treatment plants and becomes less important when the treatment plant can deliver an essentially constant supply of digested sludge slurry for disposal. On the other hand, pipelines have inherent capacity for increased capacity over their lifetimes. Additional quantities of materials can be moved, generally by increasing the pumping stations and moving the material at increased velocities.

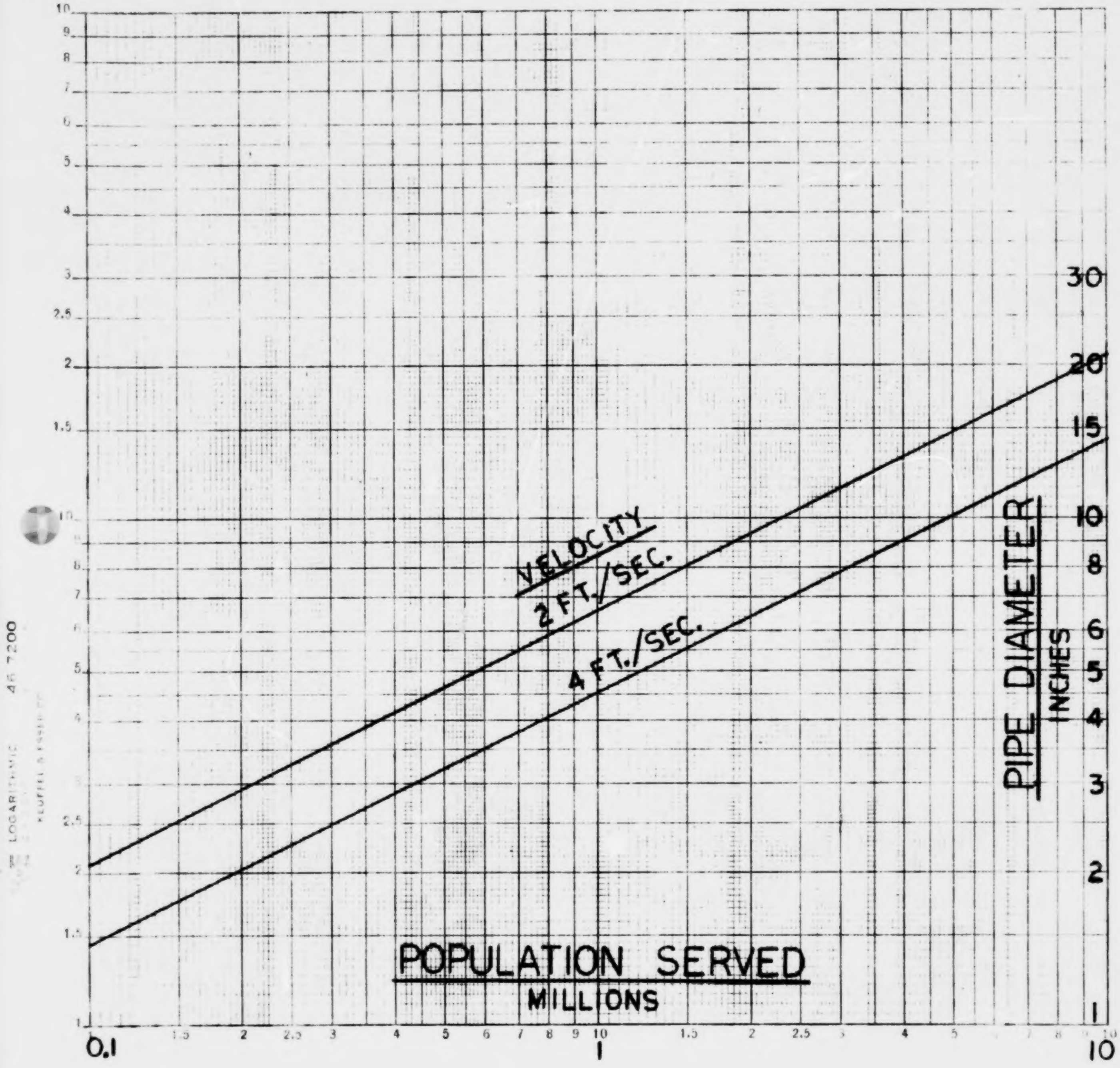
Some pipelining costs are more or less independent of the kind of material being pumped; other costs are influenced by the material being moved, or the design of the line. In the first category are pipeline rights of way costs, legal fees, required capacity and even length of line. In the second category are costs which are a function of special requirements (such as prevention of plugging) imposed by the fluid in the transport of sludge slurries which directly influence pipeline costs.

The first of these special requirements is the quantity of solids and of liquid to be moved. Sludge slurries as produced in present sewage treatment practice vary considerably in concentration from a few percent solids to perhaps

15 percent. While the relation of quantity to be moved upon pipeline design capacity is easily visualized, there are other less obvious influences. The velocity at which material moves bears directly on pipeline diameter and on power costs. Figure 3 shows the influence of doubling fluid velocity upon pipeline diameter. The effect upon power costs is more subtle. Pipeline construction costs vary almost directly with pipeline diameter, about doubling as the pipeline diameter doubles - quadrupling the capacity. The influence of fluid velocity upon costs, power and capital costs, is a separate matter, and one of particular interest when the fluid is digested sludge slurry.

FIG. 3

Pipe Sizes for Transport of Sludge at Five Percent Solids



III - DISCUSSION

The disposal of digested sludge solids alone, when accomplished by the conventional sewage plant operations of filtration and incineration; incurs about half the cost of sewage treatment.

Pipelining of digested sludge slurries, even over long distances, with disposal of the solids upon the land was shown in the first phase of this work(1) to promise a more economic means of dealing with these solids. More than that, the digested sludge slurries can be put to use to reclaim and restore stripped land areas.

The quantities of digested sludge slurries which are produced in small cities are such that small diameter lines are required to achieve the full economies for disposal promised by this disposal concept. Reservations are expressed in the literature about the use of small diameter (under 4-inch diameter) pipes to conduct sludge slurries (35, 36). In order for the pipelining concept to achieve its maximum acceptance, the concern for using small diameter pipelines needed to be examined.

The reservations have been examined, and as a result, the use of pipelines of small diameter can be recommended. Two aspects required examination. The first aspect relates to the feasibility of the use of small diameter lines and their being able to maintain flow of sludge slurries. The second aspect has to do with the costs of operating a sludge slurry line. Both of these considerations relate to the description of the fluid flow characteristics of digested sludge slurries, and relating those fluid flow characteristics to those of fluids being transported economically in operating pipelines today.

The most prominent literature concerned with the flow of digested sludge slurries in pipes does not spell out what can be expected in small diameter lines. It has not been important in conventional treatment practice to elucidate this behavior, and most experience has been confined to large diameter pipes, in-plant lines, and difficulty in moving high solids content sludges in small lines at low velocities. For long distance transport a particular consideration is the determination of the maximum solids concentration slurry which allows fully turbulent flow at velocities set by economic construction cost. Anticipation of a maximum concentration was given by Chou (37), who described a transition from newtonian to plastic flow as a function of solids concentration. Another consideration is fluid friction head loss, which can be related to the experience and technology of pipeline design.

A. Fluid Flow of Sludge Slurries

As stated, the hydraulic characteristics of sludge slurries are not described in the literature with the precision needed for satisfactory economic pipeline transport design. The literature contains such statements as: "Velocities of flow between 5 and 8 feet per second are, in general, found to be satisfactory . . ." for the transport of sludge slurries within treatment plants. Such descriptions of sludge slurry flow may be appropriate for plant operation, but are inadequate for economic long-distance flow description. A change in velocity from 5 to 8 feet per second is a 60 percent increase in rate. But, if the fluid were water in turbulent flow the increase in friction head loss would be about 140 percent, or more than double. What the increase is for sludge slurries is of design importance . . . In this work, the characteristics of sludge slurries as they relate to economic pipeline transport have been elucidated and measured sufficiently for design purposes.

The hydraulics of digested sludge slurry flow is more complicated than that of typical water slurries because a sludge slurry may be either newtonian or plastic as a function of its solids concentration. Sludge slurries change in nature from a newtonian fluid like thin water slurries to a Bingham-type or plastic fluid when their solids concentration is over about 5 percent. This change dominates some design considerations. (Results of this work indicate 5 percent, whereas Chou estimated a 4 percent average. The 5 percent figure is approximate and varies to some extent with different slurries, but is precise enough for use in this discussion and is in line with other investigators (38).) A simple test to determine this concentration in a sludge slurry is described later.

The important determination for sludge slurry pipeline design is the minimum velocity which permits turbulent flow. Turbulent flow is needed to keep settleable solids in suspension. The minimum turbulent flow is desired, because velocities in excess of the minimum increase pumping power expense. This limitation does not apply to water or to slurries with only 1 or 2 percent solids, in which turbulence occurs at extremely low velocities. In such fluids the economics of pipeline capital costs versus pumping or operating costs indicate operation at velocities in excess of the minimum required to produce complete turbulence.

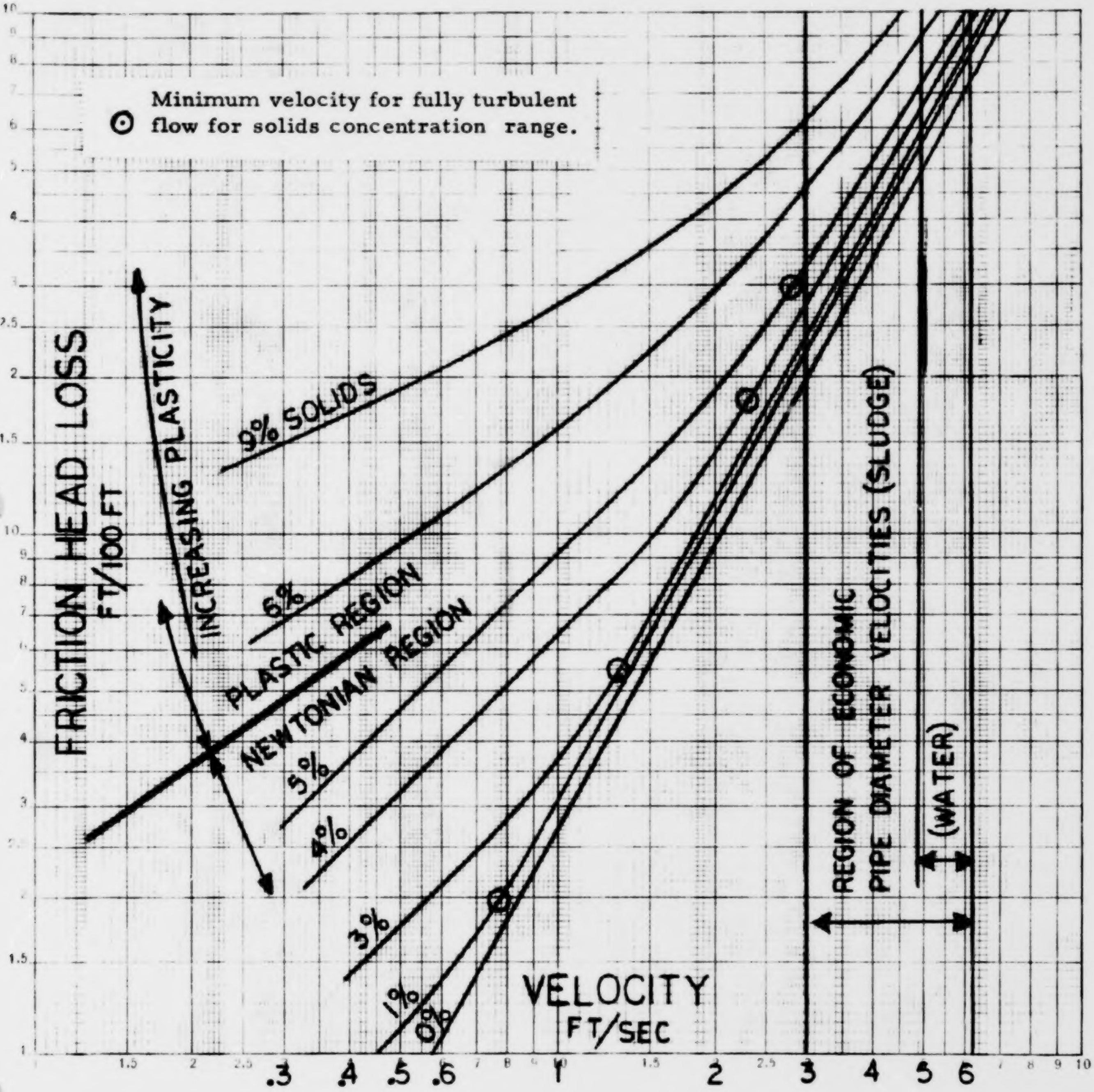
The accompanying Figure No. 4 is a visual presentation of the friction head loss data obtained in the present examination of sludge slurry flow in small diameter pipe. Friction loss as related to newtonian and plastic flows, solids concentrations, and velocities are shown. Typical data are given in Appendix "A". The transition between laminar and turbulent flow is shown in the interval where changes from typical laminar slope to fully turbulent velocity slope occur. Fully turbulent flow occurs at the velocity at which the head loss becomes linear and substantially parallel to the turbulent water friction head loss curve. Similar data for water are given for comparison. The economic transport velocity range for water, taken from the literature, is shown (39) and the economic velocity for 5 percent solids sludge slurry is also indicated.

As solids content in the slurry increases from 0 to about 5 percent, the flow rate or velocity at which the transition from laminar to turbulent flow occurs also increases. Up to about 5 percent, the transition is abrupt. The figure indicates that in sludge having a solids concentration of about 5 percent and in small diameter pipes, the velocity at which the transition occurs is approximately that at which water is economically pumped. When the quantity of sludge to be pumped is also known, the economic pipe diameter is easily fixed. Because complete turbulence should be assured in slurry transport to reduce operating problems such as settling, reliable practice will frequently call for velocities somewhat above the minimum required to achieve complete turbulence.

FIG. 4

Stylized Diagram

Influence of solids concentration in sludge slurries upon minimum velocities at which fully turbulent flow is achieved. Friction head loss is shown, and the region of velocities in which fluids are generally economically transported is indicated



It can be seen that to maintain complete turbulence for solids concentrations above 5 percent, the velocities are greater, and the transition from laminar to turbulent flow is more gradual, and not so easily pinpointed. The accompanying friction head losses may increase so rapidly as to more than offset any economic advantage to be gained by pumping the higher solids material, despite a reduced volume of material handled. This latter general statement holds for all pipelines but those serving the large populations in the country because minimum velocities for turbulence decrease with increasing pipe diameter, and in the 10 to 20-inch diameter range turbulent flow can be achieved below the economic velocity region.

B. Flow Character of Plastic Materials in Pipes

An exact analysis is useful for describing the differences in the nature of the transition region from laminar to turbulent types of flow between flows of viscous materials and of plastic materials. For newtonian materials, turbulence is initiated at the center of the pipe, and as the velocity is gradually increased, in a given pipe, the turbulent region expands towards the wall from the center, continually increasing in degree and moving outwards until the total pipe diameter cross section becomes turbulent up to the walls.

With plastic materials the flow in the laminar, transitional and turbulent regions is markedly different. For plastic sludges some definite finite value of force or pressure must be applied in order to obtain any flow at all. Flow occurs first in the center of the pipe and that flow decreases in velocity from the pipe center to the pipe wall. That is, the flow in the center is always faster than in any other portion of the pipe cross-section. Some sludge next to the pipe wall will not move, even with high average volume flow. The first flow initiated in the center of the pipe will probably be laminar. The laminar portion will gradually extend further and further towards the pipe wall with increase in total average velocity, and before laminar flow is obtained all the way to the pipe wall, turbulent flow will be initiated in the center of the pipe. Turbulent flow will then expand towards the pipe wall and the result will be turbulent flow in the center with laminar flow around or outside the turbulent portion. For some finite distance from the pipe wall inward there will be no flow at all. It will be seen that this concept implies that there is no sharp end point to the laminar flow region in terms of average velocity over the whole cross-section of the pipe, and there will also be no sharp end point for the transition region, as is found in newtonian material flow. In fact, for plastic fluids, the fully turbulent region approaches full turbulence only asymptotically, and in some sense, with rough pipes at least, will never be precisely reached. Therefore, the head loss friction measurement related to the average velocity in pipe flow for a plastic fluid will not have the inflection points which are present in newtonian material flow curves, nor will it quite show the straight line curve for head loss against velocity on logarithmic paper in the fully turbulent region to the extent that newtonian flows show.

The necessity for turbulence has already been considered, but finding the flow rate where turbulence occurs depends on the nature of the fluid pumped as well as pipe size and roughness. For the purpose of this discussion there are two distinguishable sludge types of fluids; the newtonian or nearly newtonian and the plastic type.

For an appreciation of the problem in relating a fluid flow type, newtonian or plastic, to the requirement of turbulence - refer first to Figure 5.

The lower left hand corner of Figure 5 displays the response of a newtonian fluid to the application of a small force. Notice that the line rises from the corner of the graph to indicate that a small force will induce a proportionately small flow. Furthermore, the ratio of force to flow rate is substantially linear both in the laminar flow region which is to the left of the break, and in the turbulent flow region which is to the right of the break in the graph line. The break in the graph represents an area of transition where both some laminar and some turbulent flows exist together.

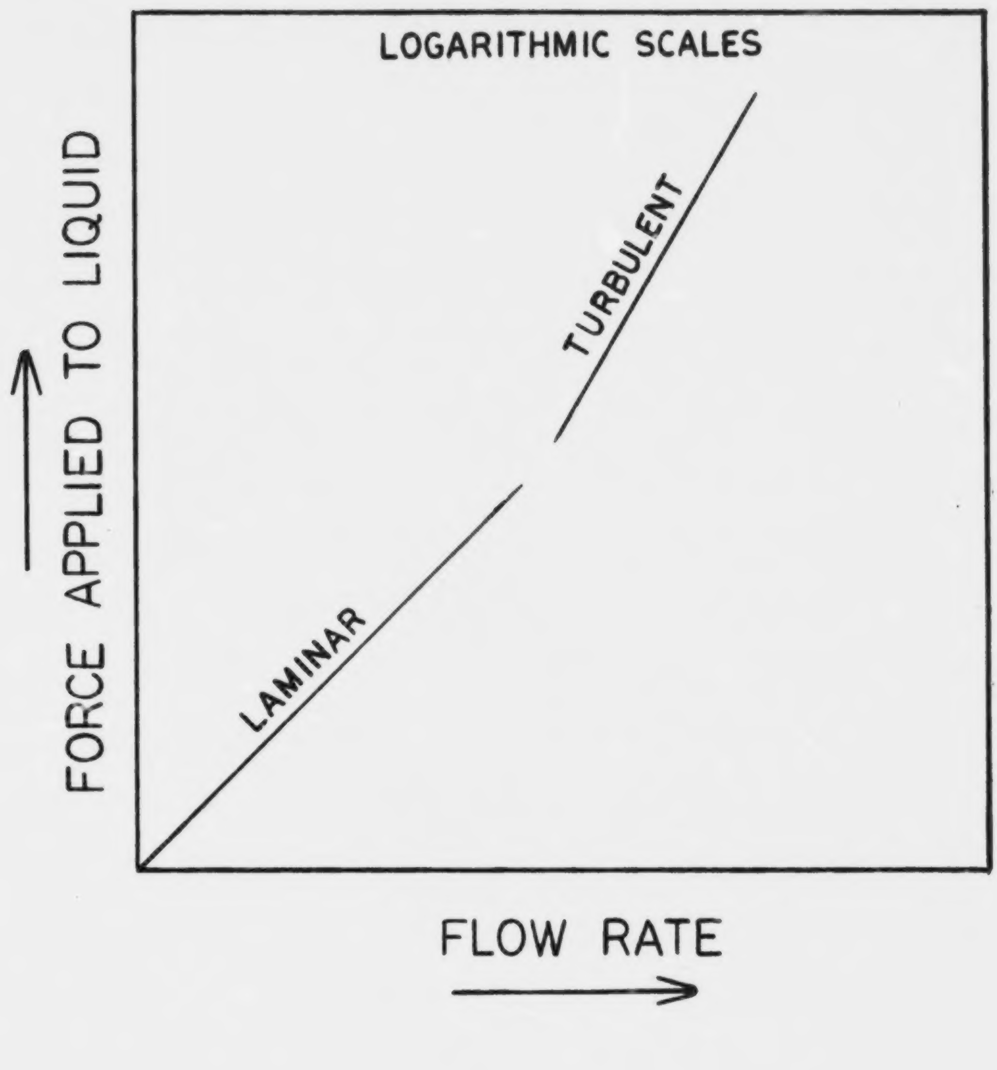
A more important property disclosed by Figure 5 is the slopes of the graph lines in the laminar and turbulent regions. The steeper slope of the line in the turbulent region indicates that a proportionately greater force must be applied for a unit increase in flow rate than would be necessary for comparable unit increase in the laminar region. The important implication of this factor is that where turbulence is necessary, it will be most economic to use the minimum force required to achieve sufficient turbulence. Increasing the flow rate unnecessarily in the turbulent region will require heavy increases in expenditures of power which earn only small increases in flow.

Figure 6 illustrates a plastic fluid and its graphic response to force. The following comparisons between newtonian and plastic material flows should be noted:

1. For plastic materials (and high solids content digested sludge is such a fluid) flow does not begin with the least application of

FIGURE 5

FLOW OF NEWTONIAN TYPE MATERIALS



force. Force can be applied without inducing flow until a certain maximum force is reached (see points "A", and "B" on Figure 6). This is a property which defines plastic "fluids".

2. For sludges of moderate or high concentration (roughly those in excess of 5 percent solids) a sharp break in the graph line will not occur to indicate the transition point from laminar to turbulent flow. In fact, for high solids content sludges the change in slope is so gradual that by the time the region of complete turbulence is reached the force required may be economically prohibitive for the smaller diameter lines.

3. Low solids content sludges (5 percent solids) received as a process product or through dilution of a heavier material will have a determinable turbulent flow region in an area where a reasonable and economic pumping force can be applied for even small diameter lines.

In the following section a simple test will be described that can distinguish when a sludge is behaving as a plastic fluid. In addition, this test can advise an operator as to a dilution ratio which will make the sludge slurry either slightly plastic, or newtonian.

A plastic "fluid" - sludge slurry above 5 percent in solids concentration - has the characteristic of being able to resist flow. Plastic "fluids" require power to achieve any flow at all and more power for flow in the laminar region than do newtonian fluids, until turbulence is achieved. In the gradual transition region from laminar to fully turbulent flow, the change in velocity may be a factor of 4 or 5 while friction head loss is the 1.8 power of velocity change. The incident effect is upon the pipeline capacity at a given power input. The change from newtonian to plastic-type fluid flow, in sludge slurries, is likely to occur at a varying solids concentration level and to be some function of the ratio of volatile-to-fixed solids. Temperature has an effect on viscosity and therefore on the velocity at which the transition from laminar to turbulent flow occurs, and therefore upon the relation to friction head loss. Over the range from 40°F. to 80°F., tap water changes its relative viscosity by a factor of almost 2. This factor could require a change of some two times in velocity to achieve turbulent flow, and result in an increase of from three to four times in friction head loss. Economic pipeline design becomes a cost optimization of all the major variables.

The concepts presented in this section are based on the data and theory appearing in references 40 through 71.

C. Sludge Slurry Flow Characteristics

The minimum velocity at which turbulence is developed in pipes conducting a newtonian fluid is logarithmically inversely proportional to pipe diameter. The hydraulic friction head loss at the velocity at which turbulence occurs is an inverse power function of pipe diameter as well, the exponent varying from 1.7 to 1.9. The table below gives the values for water as a function of pipe diameter (72).

TABLE II

Water Turbulent Flow

Pipe Diameter Inches	Velocity, Minimum for complete turbulent flow - ft. /sec.	Friction Head Loss ft. /100 ft. of Pipe
1	0.56	0.2000
2	0.28	0.0300
4	0.14	0.0040
8	0.07	0.0004

Since pumping power is a direct function of the force required to pump, it can be seen that pumping water in a 1-inch horizontal pipe requires 500 times as much power as in an 8-inch pipe. This is patently an oversimplification of a practical pumping situation.

Referring back to Figure 4 it can readily be seen that the minimum velocity for turbulent flow in water and watery slurries (up to perhaps 2 percent solids) is very low, far below the literature recommended economic ranges of 4 to 5 feet per second. However, the capital costs for large pipe are so relatively high as to make higher power costs for small pipe economical.

This economic consideration holds too for the pipelining of sludge slurries. In design, the large diameter pipes are not the most economical for slurry transport, all other design factors aside, especially to accommodate the limited quantities of slurry produced by small municipalities.

The minimum velocities at which turbulent flow of sludge slurries is achieved is not described adequately in the literature. Therefore, some slurries obtained from operating sewage treatment plants were caused to flow at selected velocities through 1-1/2 and 2-inch diameter pipes in a test device. These diameters are of particular interest to the many small sewage plants in the country. It is important to know that slurries can be pumped in such small lines in an economical manner. Friction head losses were determined over the range of solids drawn in Figure 4.

Data on dilute slurries under 4 percent solids content and at low velocities were not taken in detail because their economic pumping will be done at velocities well above the minimum turbulent flow velocities. For example, data obtained for a 4 percent solids slurry show that in a 2-inch pipe, turbulence was obtained at 2.3 feet per second. This velocity is below the range recommended in the literature by many authorities for economic transport of watery materials, largely, as indicated, because of pipeline capital costs. Since one would not therefore design at minimum turbulent flow in the 4 percent solids concentration range or for thinner slurries, there was no further need to pinpoint the velocities for minimum turbulence. It is possible, in fact, knowing the data for water and the minimum turbulent velocity for one point, in this case the 4 percent solids sludge, simply to calculate the minimum velocities required for turbulence from zero percent solids (water) up to the solids concentration where the nature of slurry flow becomes plastic. The table below shows the results of this calculation made using known linear logarithmic relationships between pipe diameter and minimum velocity for water and watery slurries in turbulence, and between solids concentration and minimum turbulent flow. The former relationship is shown (Table II) in hydraulic water data; the other has been defined in work on transportation of solids in pipelines, for example The Transportation of Solids in Steel Pipelines, Colorado School of Mines, 1963 (3, 4).

TABLE III

Calculated Minimum Velocity for Complete Turbulence for Sludges in a Range of Pipe Sizes and Suspended Solids Concentrations.

Solids Concentration in Per Cent	Velocity for Minimum Complete Turbulent Flow ft./sec. Pipe Diameter - Inches			
	1"	2"	4"	8"
0 (water)	56*	.28*	.14*	.07*
1	1.50	.78	.39	.20
2	2.50	1.30	.64	.32
4	4.50	2.30**	1.14	.57
5	5.50	2.80	1.40	.70

* Published Data
** Actual Data, This Work

The product of minimum velocity for turbulence and pipe diameter is a constant for constant viscosity. $VD = \mu R$, where R is Reynolds number; V is minimum velocity for turbulence, μ is apparent viscosity; D is pipe diameter. Apparent viscosity changes linearly over a small solids concentration range, (3, 73) and thus linearity holds between concentration and minimum velocity for turbulence.

It can be seen from Table III that newtonian sludge slurries flowing in about 1-1/2-inch diameter pipes carrying 5 percent solids sludges become turbulent at velocities equal to or less than practical economic velocities. For slurries under 5 percent in solids concentration in pipes larger than 1-1/2-inch diameter minimum velocities for turbulent flow do not determine pipeline design. The major design factor becomes capital cost, even at this stage in the development of pipelining sludge slurries in small (under 4 to 6-inch) diameter pipes. Any pipe size over 2-inches in diameter is completely practical, so long as protection for the pump and line from casual solids is provided.

Above 5 percent solids concentration, the plastic behavior of the slurries requires increased power to move the material because apparent viscosity is rapidly increased over that for newtonian type concentrations. Velocities required to achieve the necessary turbulence are also increased substantially. The definition of the economic break even point thus becomes somewhat more critical in pumping plastic slurries. The cost optimization process must include consideration of the high probability of increased maintenance and the power costs for pumping a heavy solids load. Although this allows pumping of reduced quantity of material, it is against higher friction head loss. The alternative is to reduce the solids content of a plastic slurry to the 5 percent level at which it flows as a newtonian fluid, and take into consideration the pumping of this increased quantity of material against a reduced friction head loss.

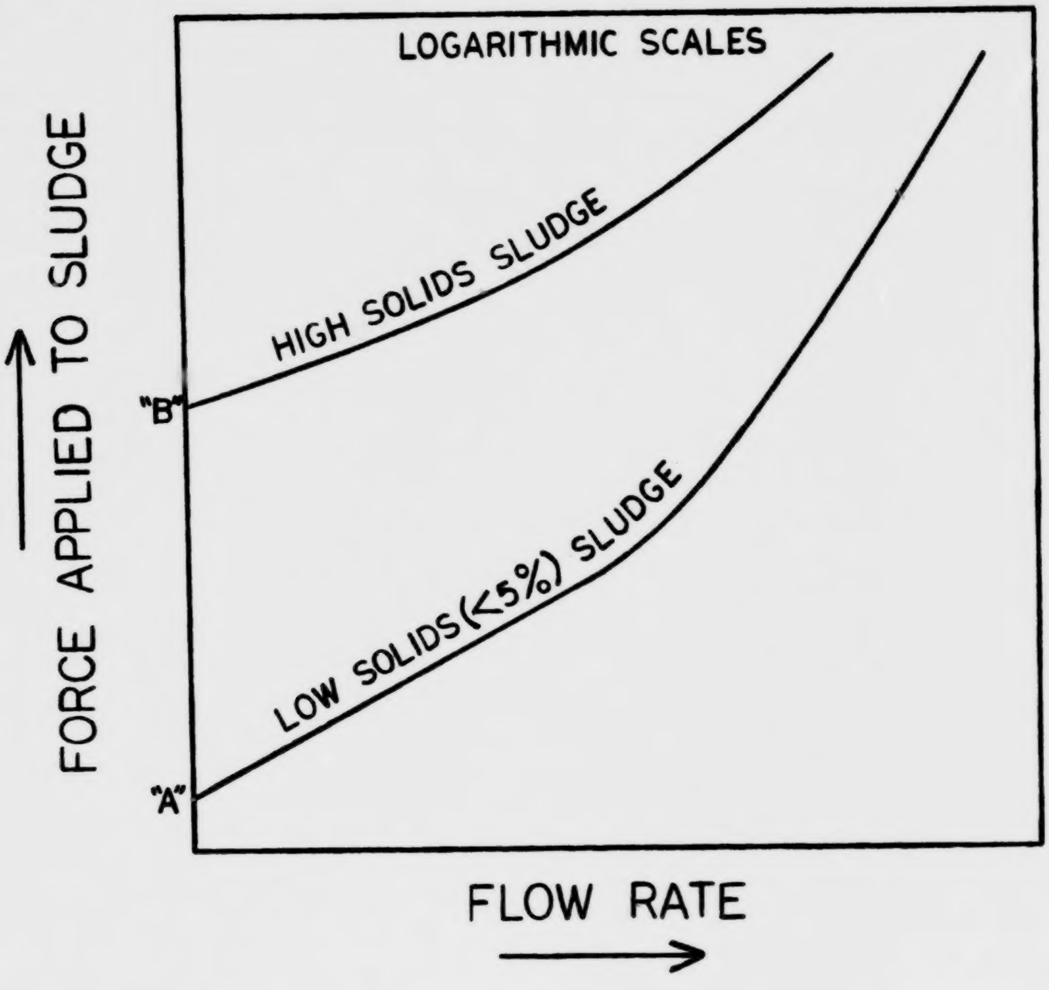
Especially to handle the slurry produced in small communities - where the design must consider small diameter pipelines - the economic choice invariably will favor dilution of plastic slurries and the design of the pipeline becomes largely dependent upon capital cost. The design becomes similar to the design of a water pipeline.

D. Simple Hydrometer Determination of Slurry Type

The change in sludge flow characteristics from a Bingham, plastic type fluid to a more nearly newtonian type fluid is of considerable interest and importance for economic pipeline transport design and for reliable pipeline operation. A description of sludges in terms of percent solids

FIGURE 6

FLOW OF PLASTIC SLUDGES



concentration alone is not expected to be sufficiently descriptive for optimum pipeline design. A simple float test performed with a hydrometer will determine the dilution required to go from plastic to newtonian properties for a given sludge.

When a hydrometer is immersed into a stirred sludge exhibiting non-plastic viscous characteristics it will provide reproducible specific gravity readings. When the fluid is plastic, however, non-reproducible readings are obtained because of the damping effect of the plastic slurry on the hydrometer float. The free oscillation of a hydrometer to an equilibrated position indicates non-plastic properties.

In effect, the hydrometer determines sludge solids content, but it responds to a particular factor, the plasticity of the slurry. Total solids determinations (residue at 105°C.) include all materials regardless of whether they contribute to plasticity. However, the hydrometer displaces only those solids suspended in the slurry.

A given solids content plastic sludge can be evaluated quickly by dilution with known increments of water and noting solids content when the hydrometer first gives single valued reproducible readings. When the range becomes reproducible the fluid characteristics have changed from plastic to newtonian and the hydrometer reading directly gives the specific gravity and indirectly the maximum solids concentration at which the change occurs. Further dilution with water gives a linear relationship between solids concentration and specific gravity for that sludge. The simple plot which results is typified as Figure 7.

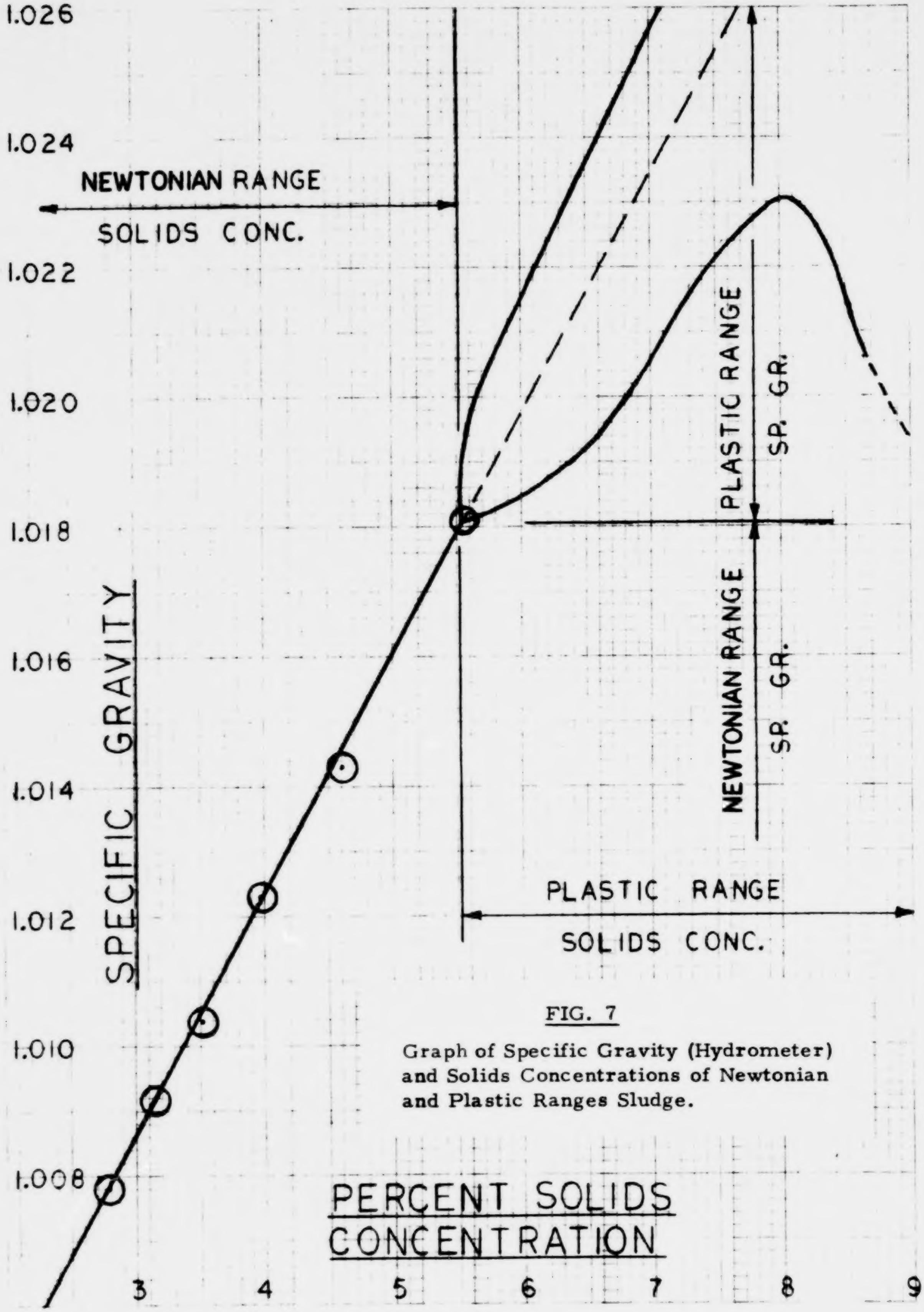


FIG. 7

Graph of Specific Gravity (Hydrometer) and Solids Concentrations of Newtonian and Plastic Ranges Sludge.

E. Pumping Test Work and Apparatus

Some digested sludge slurries were obtained from operating plants in the Cleveland, Ohio region and the flow behavior was examined in small diameter pipes in an experimental flow pumping test apparatus. The initial phases of the experimental work were carried out as a general survey of overall flow behavior and a shake-down of the set-up. In particular, it was determined that even severe bends in the piping and the required valving arrangements did not themselves induce flow stoppages.

Following this, a half dozen digested sludges were studied in detail so that friction flow head losses at a variety of flow rates and over a wide dilution range were obtained.

Actual flow and pumping tests were made through two 21-foot lengths of 1-1/2-inch pipe and two 21-foot lengths of 2-inch pipe, all four connected in series. One length of black iron pipe and one length of galvanized pipe were used for each size. In determining the friction head loss in these pipes sixteen manometers were used to indicate the difference in pressure over 8-foot distances. The connections of twelve other manometers were arranged to indicate when the measurement could be in error. Errors can result from air bubbles in the manometer feed line or from plugged or defective pressure sensing orifices in the test pipes. Provisions were made to prevent these errors or to correct them when they occurred.

A minimum counter-flow of clean water was supplied to each pressure sensing orifice to prevent or reduce plugging while sludge was flowing in the pipes. The source of this flush water was a 40 gallon tank having a pressure regulated outlet. To avoid the possibility of this water influencing the manometer readings a needle valve at each orifice was used to adjust the flow to a given rotameter indicated value. This total flow amounted to 12 to 15 gallons per hour for all twenty-four orifices used.

Water supplied to the orifices also served as the medium by which pressures within the test pipes were transmitted to the manometers. Manometer feed lines were installed with considerable slope and with a distinct high point between each orifice and its manometer. A trap and bleed was provided at this point to provide for the release of any air bubbles which might enter the line.

Velocity of sludge slurry flow was varied over the range of interest. The method used for control of velocity can be readily seen from Figure 8. Pressure drops were measured across the pipe sections, and from end points to the mid-point of the line.

Two manometers measured the head losses at each end of each test pipe length. On each pipe length four manometers measured friction head losses over two precisely determined 96-inch lengths. The orifices were located opposite one another, and additional manometers were provided to indicate pressure loss across the pipe diameters. These latter manometers do not indicate friction head loss, but serve to indicate any errors in friction head loss readings or errors due to any irregularities in the flush water supply such as may be caused by partial clogging of the sensing orifices or errors due to defective orifices.

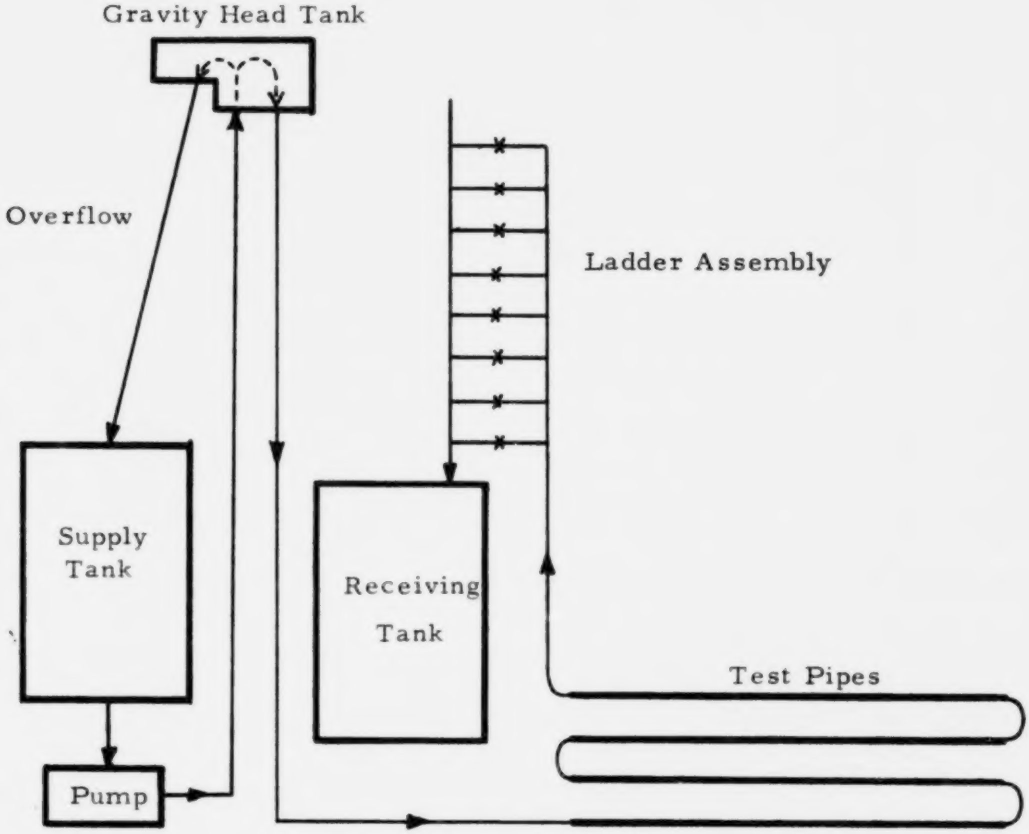
Sludge from the 350 gallon supply tank was gravity fed to the pump below the tank. It was then pumped to a gravity head tank mounted about 20 feet above the test pipes. An outlet in this vessel was used to supply the test pipes. By this method any fluctuations in the output of the centrifugal pump (Wemco Model A) were eliminated before reaching the test pipes. An overflow was provided in the gravity head tank to ensure a constant liquid level.

The sludge from the gravity head tank flowed by gravity into the series of test pipes. The space available for this work required that the pipes be mounted in vertical steps, with "U" fittings between levels. On leaving the fourth test pipe in the series the flow was taken overhead into a pipe and valve assembly, which somewhat resembles a ladder. That is, there are two vertical pipes having a series of horizontal "steps" between them. Each of these eleven steps has an on-off valve. The sludge rose past all the closed steps until it reached one having an open valve. It then flowed across to the other side of the "ladder" and fell without a siphon effect on the test pipes through the second vertical pipe into the receiving tank. The difference in elevation between the "step" and the level of the gravity head tank is the pressure or head applied to the sludge. The rate of flow through the test pipes was determined by timing the ascent of a float-mounted scale in the receiving tank. During operation the scale together with an electric clock was photographed to form a permanent record.

Differential manometers were used to measure the friction head losses. The manometers were all brought to one panel board and also photographed for simultaneous data collection and reference. Flow velocities in the test pipes

FIG. 8

Simplified Diagram of Pumping Study Test Apparatus


Gravity Head Tank
Overflow
Ladder Assembly
Supply Tank
Receiving Tank
Test Pipes
Pump

were plotted against their respective head loss figures for various solids content sludge slurries. Experiments were conducted on nine different digested slurries produced in a variety of sewage treatment plants near the Cleveland area. The data was used to generate families of curves for the various solids concentrations which were tested, as shown in Figures 9 and 10; water data taken from runs made in the test equipment are also plotted on the graphs.

FIG. 9

Friction Head Loss at Velocities of 1 Foot to 4 Feet Per Second in 2-Inch Diameter Pipe for Sludge from 2 to 13 Percent Solids Concentration. See Appendices "A" and "B".

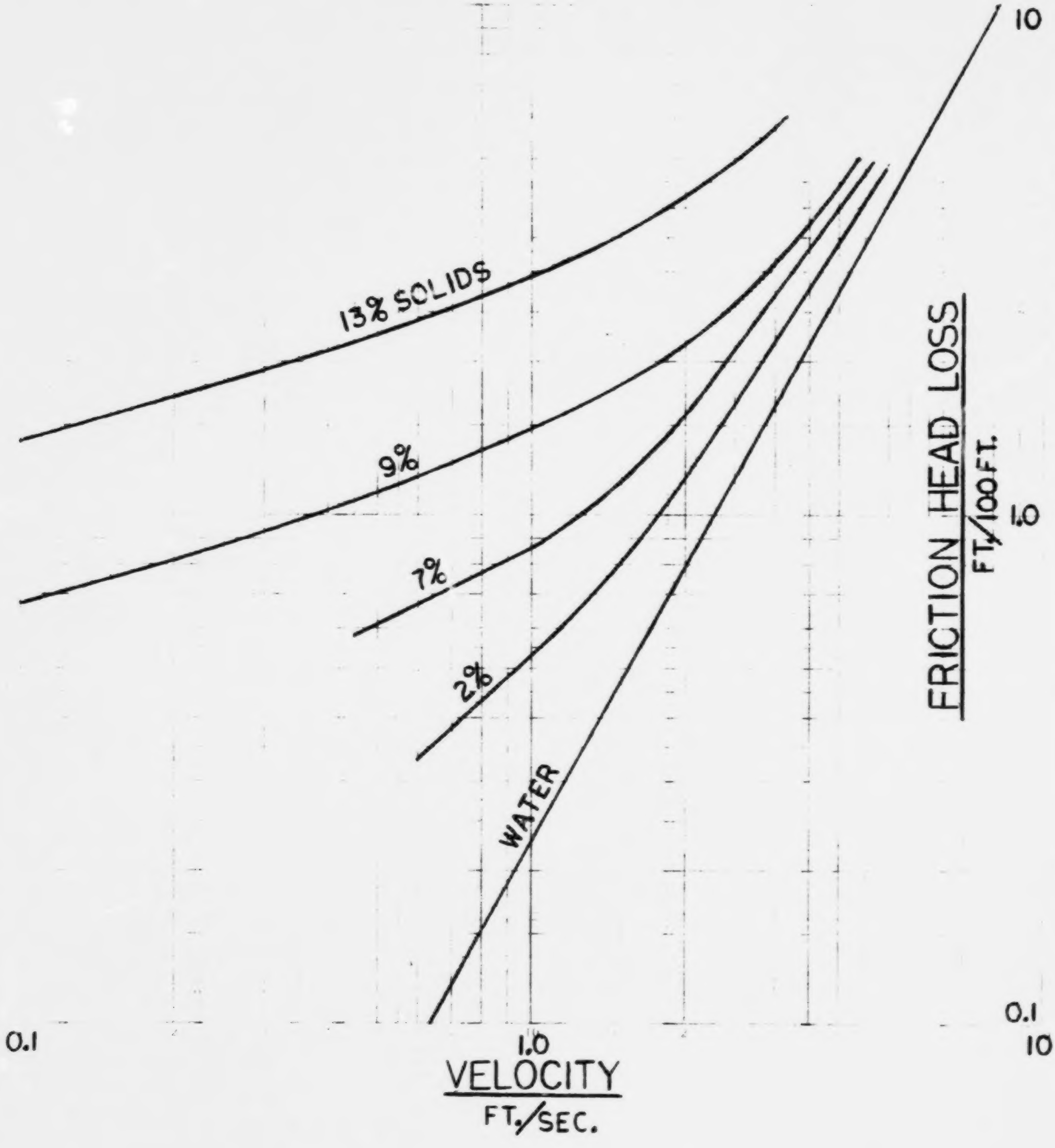
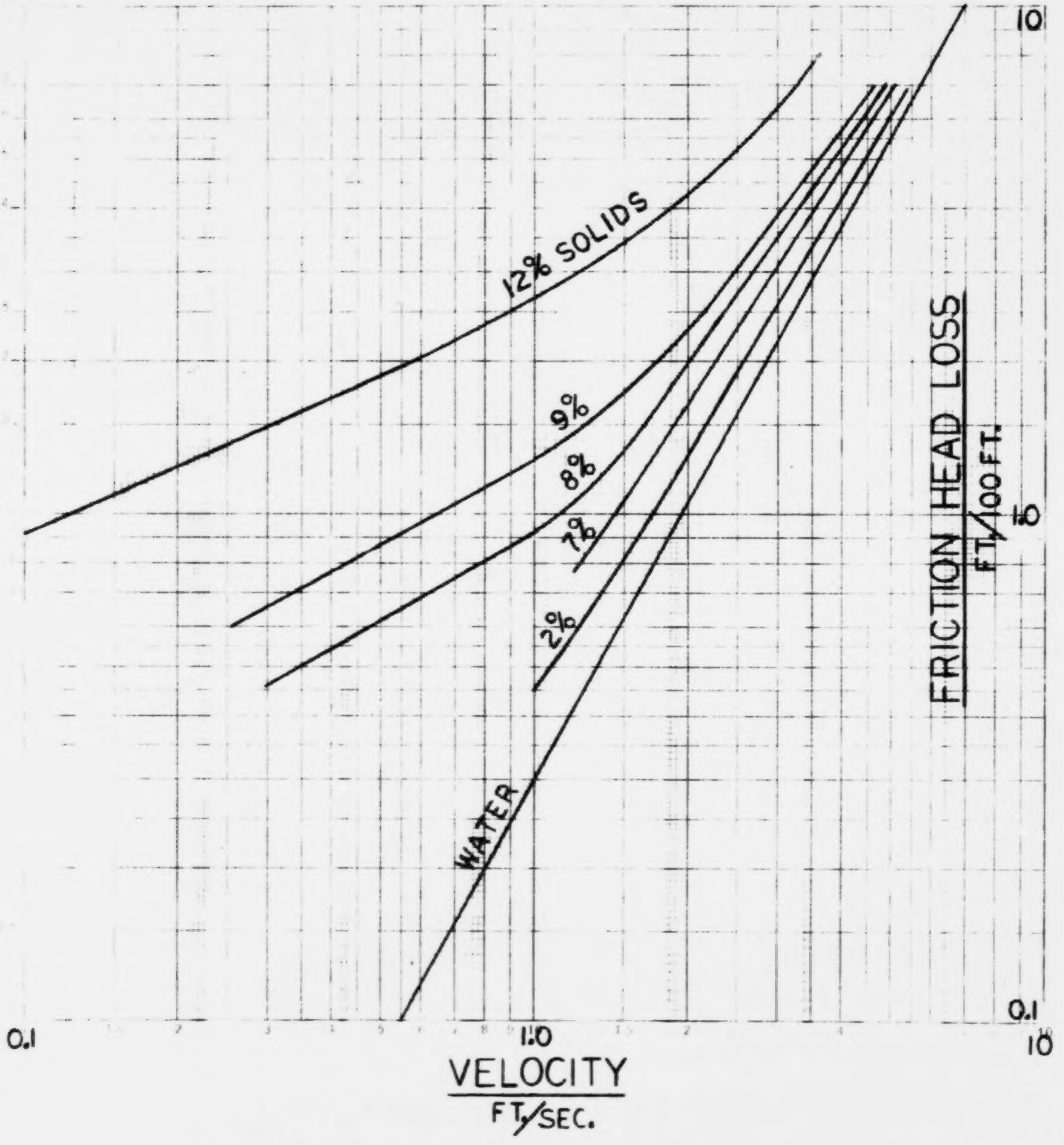


FIG. 10

Friction Head Loss at Velocities of 1 Foot to 4 Feet Per Second in 1-1/2-inch Diameter Pipe for Sludge from 2 to 12 Percent Solids Concentration. See Appendices "A" and "B".



F. Testing Procedure

A total of nine different digested sludge slurries were obtained for test from various primary and secondary sewage treatment plants in the Cleveland, Ohio area. In each case the slurry was transported by tank truck to the test pumping apparatus. There the sludge was unloaded into 55 gallon drums for temporary storage. If the sludge were known to be dilute (under 7 or 8 percent solids concentration) it was allowed to settle until supernatant could be drawn off. This simple method increased the solids concentration, making it possible easily to test a given sludge over a wider and higher range of concentrations. During pumping tests the water supplied to the test orifices very slowly dilutes the slurry. Photographs of the pumping apparatus are presented as Figures 11 and 12.

Concentrated sludge was then transferred by pump into the supply tank. There it was thoroughly mixed by passing it through the Wemco pump and through the recirculating return, and sampled. The flush water counter flow to each manometer orifice was then checked and equalized in volume. One of the gravity head steps was chosen and opened to set the flow rate for the particular test run. All manometers were checked to be sure that no air bubbles in the manometer lines were interfering with the pressure readings and introducing errors and that all orifices were performing normally. Flow through the test pipe lengths was then initiated, either by turning on the Wemco or by diverting the circulating flow.

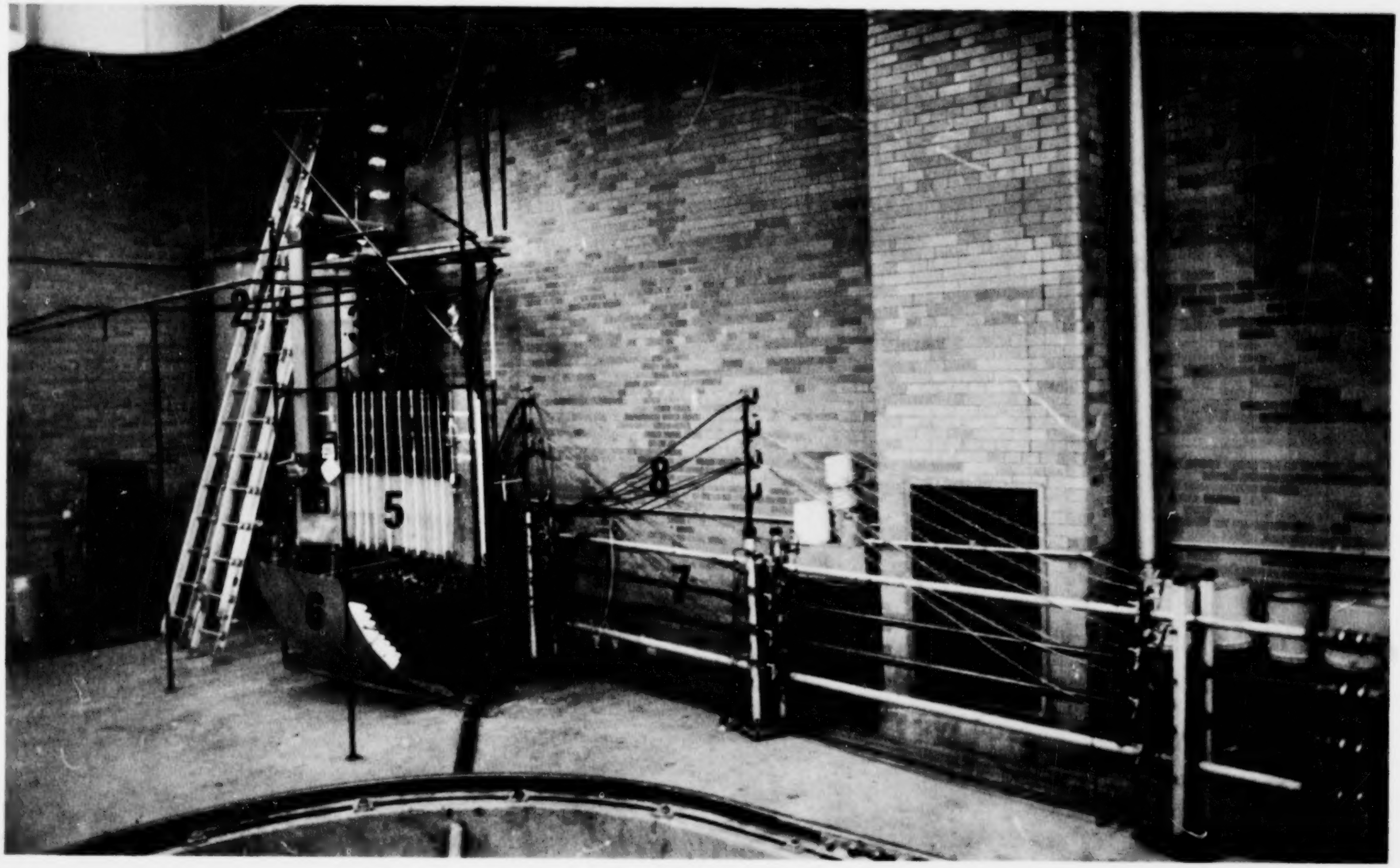
When the flow rate becomes stabilized, as indicated by a "steady board" - "stable manometers" - run data were recorded on film. Two cameras, operating at selected time intervals of 10 to 60 seconds, recorded the manometer board and the float-mounted scale and clock in the slurry receiving tank, the orifice water pressure, the sludge identity and the date. At the completion of a run, usually after some three minutes, another sample of slurry was taken.

The data were read from negatives under a binocular microscope, and tabulated. Conversions of the manometer readings were made to friction head loss in feet per 100 feet. Rates of flow were converted from inches of slurry rise per minute in the receiving tank to feet per second in the test pipe diameters.

Values for friction head loss for sludge slurries reported here were taken as indicated in the identical test pipes and recorded upon the identical instrumentation used to determine friction head loss on tap water. These results, tabulated in the appendix, produce straight lines in the fully turbulent region when the logarithm of friction head loss is plotted against the logarithm of velocity and of the same slope that the literature reports. Having water data in the same test equipment makes a valid comparison between slurry friction head loss to water friction head loss possible regardless of any systematic errors which the apparatus may possess. A systematic error in such an apparatus can result from interior pipe roughness characteristics or in individual pressure sensing orifices.

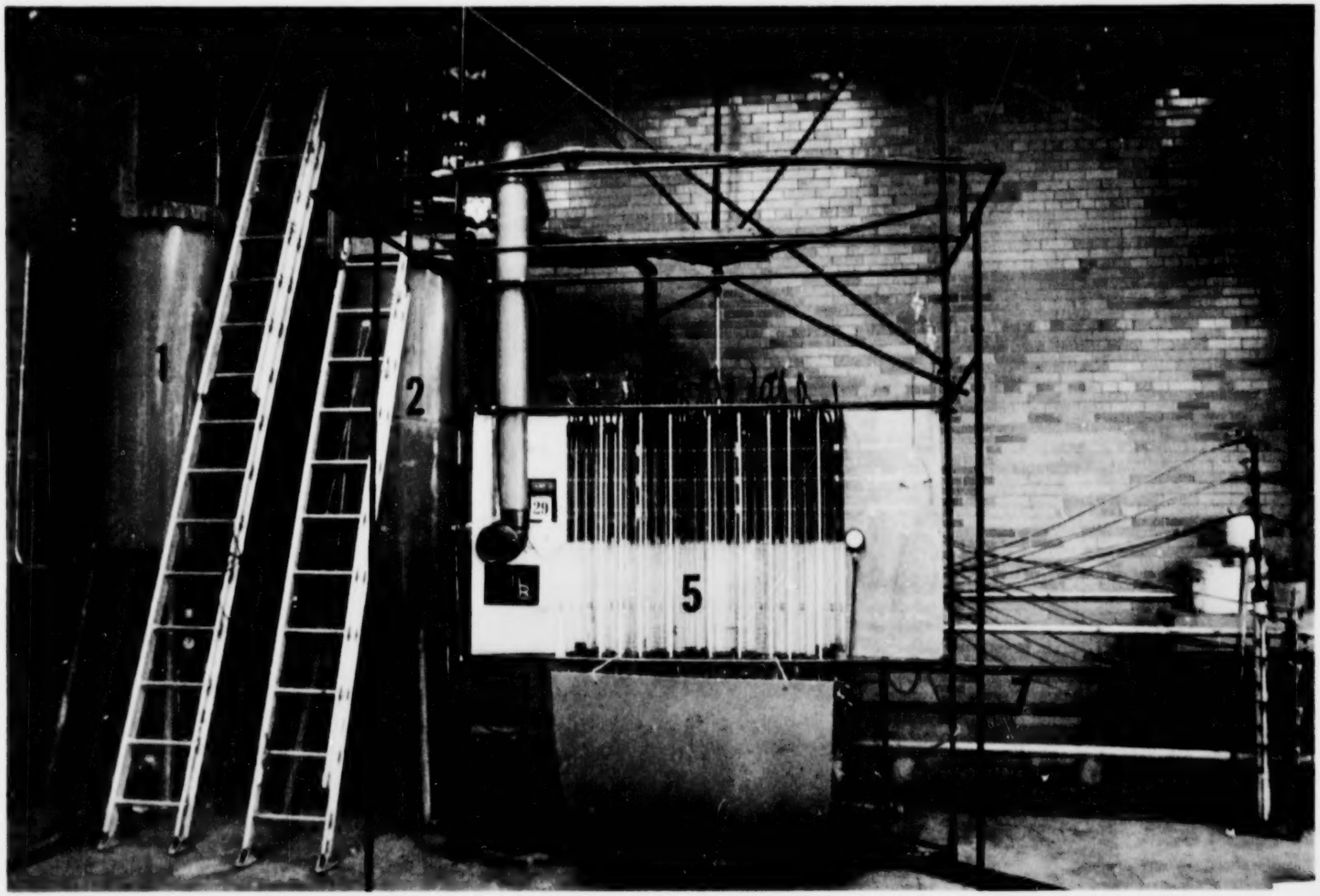
More precision can be introduced into the handling of the data presented by using the ratios of friction head losses, slurry-to-water, rather than the simple plots given here. Such precision will become especially useful in a particular study of a particular slurry.

The pumping tests described here were carried out primarily to obtain data on friction head losses developed when digested sludge slurries are



Overall view of sludge pumping test apparatus showing the following: 1. flush water supply, 2. supply tank, 3. receiving tank, 4. ladder assembly, 5. manometer board, 6. lights, 7. test pipe lengths, 8. manometer feed lines. The gravity head tank is not shown.

FIG. 11



Close-up view of sludge pumping test apparatus showing the following: 1. supply tank, 2. receiving tank, 3. pump, 4. ladder assembly, 5. manometer board, 6. scale and clock, 7. test pipes lengths.

FIG. 12

transported in small diameter pipes. A practical pipeline, regardless of its size, must also provide protection of its parts from tramp materials. This requirement is of special importance when the material being transported is sludge slurry, because the opportunity for casual solids is ever-present. In the pumping work under this contract, occasional flow decreases or stoppages occurred when high solids sludges (to 15 percent) were being studied at velocities below those which produced turbulent flow. In this limited work, hay and wire were the most troublesome tramp solids encountered. When 14 percent solids slurries were being studied at low flow rates, even sand and gravel particles were able to settle out and impair flow.

Protection of pipelines from these materials will probably be accomplished in practice either by comminution or by screening. These operations will be more easily and economically carried out on thin or newtonian slurries rather than on plastic slurries, one more reason to recommend pumping of slurries in the viscous region.

IV. RECLAMATION

Use of Sludge Slurries

The concept of land disposal of sludge slurries by pipeline transport has two parts: pipelining to a distant land disposal area; and utilization of the slurry, where possible, as a reclamation aid for such areas as abandoned strip mines. It is reported (74) that more than 800,000 acres of land have already been excavated nationally by coal strip mining activity alone, and that the rate will rise to well over 30,000 acres annually by 1970. Approximately 83 percent of the total coal and crude ore tonnage mined in the United States is produced by surface mining. Both strip and surface mining and sludge production are national activities. In ten heavily populated states, almost all major population centers are within 150 or 200 miles of coal strip mining activities. The amount of land stripped yearly is so large that the availability of sufficiently large disposal areas is seldom, if ever, an issue.

The quantity of sludge produced is dependent on the particulars of the treatment process and on the characteristics of the initial sewage. About 42 pounds of dry solids is available yearly per capita from digested sludge from primary plus secondary treatment, while about 24 pounds of dry solids is available per capita yearly from digested sludge from primary treatment only. Approximately 10,500 tons of dry solids are available from a population of 500,000 in one year if secondary treatment is used. Such a population would require the minimum availability of about 185 acres of land to dispose of a 5 percent slurry. The sludge residue would be in the order of 2" thick, at a 25 percent solids content.

This section of this report concerns fixed evaluations of the procedure as a disposal or reclamation aid and gives an estimate of the costs of disposal or restoration. It is assumed that disposal and restoration costs shall be borne by the sewage treatment interests. Despite this a substantial overall cost savings accrues to the treatment operation. Throughout this cost analysis no consideration has been given to appreciated land values resulting from the use of sludge assisted reclamation. However, a partial dollar recovery due to increased real estate values would not be an unexpected outcome in many situations.

The cost of a terminal facility and the operation of a sludge slurry disposal area for a population of 500, 000 is about $2 per dry ton of solids. This cost estimate takes into consideration grading, seeding, equipment, and manpower needed for the operation of a 185-acre disposal area. Table IV is a summary of terminal facility and operation cost estimates for six populations. The appendix to this report contains the more detailed cost estimate.

TABLE IV

Terminal Facility and Operation Costs

Population	Acres of Disposal Area Used or Reused per Year (2" Sludge Cake, at 25% Solids and 75% Moisture)	Costs Per Acre	Costs per Dry Ton
125, 000	45	$400	$6.90
250, 000	93	200	3.35
500, 000	186	115	2.05
1 million	372	90	1.65
2 million	744	70	1.25
4 million	1, 500	70	1.25

(Cost basis presented in Appendix "C".)

Field demonstrations were undertaken to show the value of disposing of digested sludge slurries to acidic strip mine areas as aids to their restoration without introducing health or nuisance concerns. In practice, using sludge slurries as obtained randomly from a municipal sewage treatment plant, application was fast and direct, and contamination related to the disposal of sludge slurries was easily and simply avoided.

Two field demonstration sites were established on coal strip mines in Pike and Sandy Townships in Stark County, ten miles south of Canton, Ohio. The choice of these sites was based on their being representative strip mines for the particular area and their proximity to Rand Development Corporation and to an available source of sludge slurry. The Pike Township site is classified as marginal, that is, the pH is below that of average soils but not so acid as to constitute a very long-term (decades) detriment to organic plant growth. Six level disposal test areas or "benches" were constructed, each approximately eighteen feet in width and one hundred fifty feet in length. Digested sludge slurry from the Canton, Ohio conventional secondary treatment plant was hauled by tank truck in 1, 000 gallon loads and was flowed from a 3-inch hose onto the benches in amounts varying nominally from 1 to 30 gallons per square foot. Solids content in the slurries varied from 1-1/2 to about 8 percent.

The Sandy Township site is classified as No. 5 spoil and is characterized by a pH 2. 8 to 3. 3 range, high dissolved salts content, and characteristic difficulty in reclamation. Normal regrowth and revegetation had not occurred in 8 years, despite legal reclamation efforts including planting of a variety of trees.

Three benches were constructed, each approximately 12 feet in width and 90 feet in length on this strip mine.

Test benches on both sites were seeded. Both sludged and unsludged surfaces were seeded with a mixture of four grasses and one legume. The four grasses were Annual Rye, K-31 Fescue, Orchard Grass, and Kentucky Blue; the legume was Bird's-foot Trefoil. The most successful method is to let the sludge weather for perhaps one or two months. Sludge has certain undesirable properties for immediate seeding since it tends to form a hard surface which becomes relatively impervious to germinating seedlings. Seed which is placed on top of freshly deposited sludge becomes isolated from the main sludge cake and cannot germinate easily. On the other hand, if the seed is put down on the ground and then covered entirely with the sludge the seed will germinate but may be unable to penetrate through the body of the sludge. After a short period of aging the surface will still be somewhat hard, but as protective cracks appear throughout the mass of the material, seeds germinate successfully.

Vigorous grass and legume growth was obtained wherever sludge cakes of at least 1 to 3 inches were deposited. Tomatoes and melons contained in sludge as seeds also flourished. The sludge slurry apparently acts as a mulch, a suitable moist environment for seed germination, a provider of nutrients and, to some extent, a neutralizer for acid-producing minerals in the spoils. This latter is demonstrated by the increase in pH of the spoil immediately beneath the sludge cake. See Table V.

TABLE V

pH of Sludge, Sludged Spoil, and Untreated Spoil

Test Bench No. & Location	pH of Sludge	pH of Spoil Immediately Under Sludge	pH of Adjacent Unsludged Spoil
Pike Township			
1-1	7.82	6.12	4.90
2-1	7.78	5.52	4.00
3-1	7.41	5.05	4.88
4-1	6.40	6.30	6.10
6-1	7.02	3.48	3.34
Sandy Township			
1-1	5.57	3.33	2.85

Sludge appears to be an excellent material to assist in the restoration of coal strip mine lands and similar unvegetated or surface mined land areas.

Moisture is extremely critical to the germination of seeds and the growth of plants. On the marginal land any mulch - whether it be sludge or straw or some other - will encourage some growth. Small depressions such as those made by a footprint or the wheels of the slurry delivery truck are sufficient moisture collecting points to encourage a sparse growth of plants. Even the shade and protection furnished by a rock can provide sufficient moisture collection to encourage growth of plants. On sludged areas, decidedly superior and even prolific growth was displayed. Moisture electrodes installed under the various benches indicated that below 3-inch sludge cakes 100 percent moisture was available in the mine spoil, while moisture near the wilting coefficient was displayed on unsludged benches. The wilting coefficient or critical coefficient is defined as the point where the water remaining in the soil is found only in the smallest of the micropores and individual soil particles.

In this form sufficient water is not available to plants; this point is usually about 20 percent moisture. On very acidic lands the sludge layer performs the function of moisture retention and also appears to neutralize at least the immediate spoil surface with which it is in contact. Spoils which are so acidic that seeds spread upon them char, can be made to initiate and sustain grass growth when enough sludge slurry to form perhaps 2 to 3 inches of cake is deposited thereon.

The growth of the legume and all the grasses, except Kentucky Blue, was successful on all the sludged benches. However, this growth was scattered among the tomatoes, melons, and some volunteer growth that covered the ground. The initial slurry application was made in June. By the winter, all the tomatoes, melons, and annuals disappeared. The grasses, legume, and some volunteer plants remained in scattered, but large, healthy clumps. During the next spring, however, new grasses were germinating and growing among the existing clumps of grasses. This new growth developed from seeds of the plants from the previous year. By June there was a vigorous grass growth 2 to 4 feet in height on the uniformly sludged areas. On areas with little sludge there was a vigorous and dense Bird's-foot Trefoil growth. On the partially sludged areas, growth was excellent where sludge was deposited, with little or no growth except sparse natural growth on unsludged areas. There was no growth on control unsludged benches that had been identically seeded.

The root penetration of these plants went through the sludge cake and well into the spoil material. Bird's-foot Trefoil penetration went more than 10 inches into the spoil and hair roots from main roots undoubtedly go further. Grass roots penetrated more than 6 inches down into the spoil.

During July the grasses and the legume matured and a good crop of seeds ensued. By August some of the Annual Rye seeds were already germinating. Volunteer growth during the year was excellent. Several poplars planted for reclamation two years previously were growing in one of the benches. After sludge had been applied, the average growth was 8 inches in 1965 and 4 feet in 1966. The growth of other poplars on unsludged areas of the mine was less than 6 inches for this period. Although the growing season was relatively dry, the overall growth on all sludged benches was excellent.

Since the field use of digested sludge slurry to restore marginally acid strip mines resulted in excellent growth and rapid reclamation, a decision was made to demonstrate the restoration capability of digested sludge slurry on spoil more acid than that which had been previously studied. To accomplish this, four new sites were located in southeastern Ohio. These sites included spoil types and variations representing difficult reclamation subjects. Spoils composed predominately of one type of material (shale, clay, or sandstone) and mixtures of each are found at the four sites. The spoil banks selected were four to eight years old, all very toxic. The spoils are extremely acid with a pH 2.7 to 3.4 range. Although the four mines had been planted with trees, indeed some twice, the growth was either very sparse or completely absent.

In late August and early September, fifteen level disposal areas were constructed. Twelve of these were used as sludge test areas while the other three were used as control areas. Sludge was hauled in 1500 gallon loads and released from a 4-inch pipe into the disposal areas. Approximately 255,000 gallons of digested sludge slurry was used to cover a total of 45,000 square feet in the twelve benches. The digested sludge came from three sources and varied from 5.5 to 8.2 percent solids in the pH 7.0 to 8.1 range. Seeds were incorporated into the sludge during a final application. In this last operation a sludge and seed mixture was sprayed over the area in about a 1/2-inch layer through a 3/4-inch nozzle at 130 psi.

The seeds were Perennial Rye Grass, Timothy, Sweet Clover, Ranger Alfalfa, and Kentucky 31 Tall Fescue. In addition to grasses and legumes, seeds of the following trees were incorporated into the last sludge to be applied: White Pine, Red Pine, Virginia Pine, Red Gum, Black Alder, Black Locust and Green Ash.

After two weeks, the sludge had dried to the extent that it could be walked upon. Observation of thick portions of the sludge bed (2 to 4 inches) indicated most of the germination occurring at the sides or in the crevices of the sludge blocks. In places where the sludge layer was thin (1/4 to 3/8-inch), sludge flakes were thin enough to break and permit sprouting seedlings to show. After five weeks, grasses and some tomatoes were growing from the hardened sludge surface as well as in the cracks. Several days of rain had apparently softened the surface to allow seed germination and plant growth. And by this time the roots of some grasses had penetrated well over an inch into the sludge cake and into the spoil wherever the sludge cake was thin enough.

Field observations indicate that a 2-inch sludge cake depth may be adequate to restore very toxic spoils, while thinner sludge layers will be suitable for marginal spoils.

Throughout the field work there have been no objectionable odor levels; only the typical musty, soil-like odor could be recognized a few days after sludge slurry application. There was no observable increase in insect activity, specifically flies and mosquitoes; or any nuisance from the disposal of sludge slurry.

APPENDIX "A"

Data Used in the Construction of Figures 9 and 10

APPENDIX "A"

Data Used in the Construction of Figures 9 and 10

	Galvanized Pipe			
Percent Solids	Velocity ft/sec 1-1/2" Pipe	Friction Head Loss ft/100 ft in 1-1/2" Pipe	Velocity ft/sec 2" Pipe	Friction Head Loss ft/100 ft in 2" Pipe
2	7.29	-	4.43	3.47
2	6.68	-	4.06	2.95
2	6.34	-	3.85	2.76
2	5.21	6.79	3.16	2.00
2	4.77	5.27	2.71	1.54
2	3.17	2.83	1.92	0.82
2	2.26	1.54	1.37	0.47
2	1.13	0.52	0.68	0.33
7	6.90	-	4.19	3.65
7	6.51	-	3.95	3.69
7	6.25	-	3.79	3.50
7	5.86	-	3.56	3.12
7	5.73	-	3.48	2.73
7	5.60	7.75	3.40	2.45
7	5.21	-	3.16	2.61
7	4.82	7.06	3.00	2.22
7	4.94	6.80	2.92	2.30
7	4.17	5.42	2.53	1.74
7	4.03	5.36	2.45	1.83
7	3.39	3.99	2.06	1.35
7	2.60	2.26	1.58	0.84
7	1.12	0.78	0.79	0.50
8	6.77	-	4.11	3.90
8	6.51	-	3.95	3.90
8	5.99	-	3.63	3.73
8	5.64	-	3.42	3.25
8	5.08	-	3.08	2.69
8	4.94	-	3.00	2.69
8	4.69	6.98	2.84	2.28
8	3.82	5.21	2.32	1.96
8	2.95	3.18	1.79	1.81
8	1.47	1.19	0.89	1.46
8	0.28	0.50	0.17	0.52
9	6.64	-	4.03	3.38
9	6.38	-	3.87	3.82
9	5.86	-	3.56	3.40
9	5.60	-	3.40	2.71
9	5.34	-	3.24	2.64
9	4.94	7.82	3.00	2.62
9	4.94	6.87	3.00	2.26

APPENDIX "A" (Continued)

Data Used in the Construction of Figures 9 and 10

Percent Solids	Velocity ft/sec 1-1/2" Pipe	Friction Head Loss ft/100 ft in 1-1/2" Pipe	Velocity ft/sec 2" Pipe	Friction Head Loss ft/100 ft in 2" Pipe
9	3.78	4.91	2.29	2.10
9	3.12	3.27	1.90	1.87
9	1.65	1.71	1.00	1.75
9	0.13	0.49	0.08	0.67
12	4.17	-	2.53	5.38
12	4.17	-	2.53	5.05
12	4.17	-	2.53	4.72
12	3.26	-	1.98	4.31
12	3.51	5.74	2.13	3.59
12	1.82	4.72	1.10	3.02
12	0.78	3.36	0.47	2.49
12	0.41	1.66	0.25	1.93
12	0.06	0.75	0.04	1.03

APPENDIX "B"

Basic Data Used for the Computation of Values in Appendix "A"

APPENDIX "B"

Basic Data Used for the Computation of Values in Appendix "A"

	Galvanized 1-1/2" Pipe Manometer No. 5			Friction Head Loss	Galvanized 2" Pipe Manometer No. 11			Friction Head Loss
Date and Run Number	Right Inches 16ths	Left Inches 16ths	Difference Inches of Manometer Fluid Inches 16ths	Difference x Conversion Factor (0. 18158) ft/100 ft	Right Inches 16ths	Left Inches 16ths	Difference Inches of Manometer Fluid Inches 16ths	Difference x Conversion Factor (0. 18158) ft/100 ft
July 28-1	-	-	-	-	32.13	13.11	19.02	3.47
2	-	-	-	-	31.05	15.01	16.04	2.95
3	-	-	-	-	30.13	15.10	15.03	2.76
5	42.02	4.12	37.06	6.79	28.09	17.09	11.00	2.00
6	37.14	8.14	29.00	5.27	27.06	18.14	8.08	1.54
8	31.03	15.10	15.09	2.83	25.07	20.15	4.08	0.82
9	27.11	19.03	8.08	1.54	24.09	22.00	2.09	0.47
11	25.00	22.02	2.14	0.52	24.14	23.01	1.13	0.33
Sept. 1	-	-	-	-	33.11	13.06	20.05	3.69
2	-	-	-	-	32.02	14.15	17.03	3.12
3	-	-	-	-	30.11	16.05	14.06	2.61
4	43.05	4.07	38.14	7.06	29.12	17.01	12.11	2.30
5	42.10	5.03	37.07	6.80	29.10	17.06	12.04	2.22
6	38.11	9.03	29.08	5.36	28.04	18.14	9.06	1.70
7	33.12	13.15	19.13	3.62	27.00	20.01	6.15	1.26
8	30.01	17.10	12.07	2.26	25.14	21.04	4.10	0.84
9	25.14	21.12	4.02	0.75	25.09	21.07	4.02	0.75
Sept.27 1	-	-	-	-	33.10	13.08	20.02	3.65
2	-	-	-	-	33.03	13.15	19.04	3.50
3	-	-	-	-	31.02	16.01	15.01	2.73
4	45.02	2.07	42.11	7.75	30.05	16.13	13.08	2.45
9	28.07	19.02	9.05	1.69	27.06	19.11	7.11	1.40
10	34.13	12.13	22.00	3.99	27.04	19.13	7.07	1.35
11	38.13	8.15	29.14	5.42	28.05	18.12	9.09	1.74
12	25.13	21.08	4.05	0.78	25.04	21.13	3.07	0.62

Continued . . . .

APPENDIX "B" (Continued)

Basic Data Used for the Computation of Values in Appendix "A"

	Galvanized 1-1/2" Pipe Manometer No. 5			Friction Head Loss	Galvanized 2" Pipe Manometer No. 11			Friction Head Loss
Date and Run Number	Right Inches 16ths	Left Inches 16ths	Difference Inches of Manometer Fluid Inches 16ths	Difference x Conversion Factor (0.18158) ft/100 ft	Right Inches 16ths	Left Inches 16ths	Difference Inches of Manometer Fluid Inches 16ths	Difference x Conversion Factor (0.18158) ft/100 ft
Sept. 15-1	-	-	-	-	34.05	12.13	21.08	3.90
2	-	-	-	-	34.06	12.14	21.08	3.90
3	-	-	-	-	33.14	13.05	20.09	3.73
4	-	-	-	-	32.19	14.11	17.14	3.25
5	-	-	-	-	31.00	16.03	14.13	2.69
6	-	-	-	-	31.00	16.03	14.13	2.69
7	42.13	4.06	38.07	6.98	29.13	17.04	12.09	2.28
8	37.13	9.02	28.11	5.21	28.15	18.02	10.13	1.96
9	32.05	14.13	17.08	3.18	28.09	18.09	10.00	1.81
10	26.12	20.03	6.09	1.19	30.06	16.13	13.09	2.46
11	24.14	22.02	2.12	0.05	28.13	20.04	6.09	1.19
Sept. 26-1	-	-	-	-	32.14	14.04	18.10	3.38
2	-	-	-	-	34.02	13.01	21.01	3.82
3	-	-	-	-	32.15	14.03	18.17	3.40
4	-	-	-	-	31.01	16.02	14.15	2.71
5	-	-	-	-	30.14	16.05	14.09	2.64
6	45.04	2.03	43.01	7.82	30.13	16.06	14.07	2.62
7	42.11	4.14	37.13	6.87	29.13	17.06	12.07	2.26
8	37.07	10.06	27.01	4.91	29.05	17.12	11.09	2.10
9	32.12	14.12	18.00	3.27	28.11	18.16	10.05	1.87
10	28.07	19.00	9.07	1.71	28.06	18.12	9.10	1.75
11	25.02	22.07	2.11	0.49	25.06	21.11	3.11	0.67
Sept. 23-1	-	-	-	-	38.06	8.12	29.10	5.38
2	-	-	-	-	37.07	9.10	27.13	5.05
3	-	-	-	-	36.09	10.09	26.00	4.72
4	-	-	-	-	35.07	11.11	23.12	4.31
5	39.08	7.14	31.10	5.74	33.07	13.11	19.12	3.59

Continued . . . .

APPENDIX "B" (Continued)

Basic Data Used for the Computation of Values in Appendix "A"

	Galvanized 1-1/2" Pipe Manometer No. 5			Friction Head Loss	Galvanized 2" Pipe Manometer No. 11			Friction Head Loss
Date and Run Number	Right Inches 16ths	Left Inches 16ths	Difference Inches of Manometer Fluid Inches 16ths	Difference x Conversion Factor (0.18158) ft/100 ft	Right Inches 16ths	Left Inches 16ths	Difference Inches of Manometer Fluid Inches 16ths	Difference x Conversion Factor (0.18158) ft/100 ft
Sept. 23-6	36.10	10.10	26.00	4.72	31.12	15.04	16.10	3.02
7	32.15	14.07	18.08	3.36	30.07	16.12	13.11	2.49
8	28.03	19.01	9.02	1.66	28.14	18.04	10.10	1.93
9	25.11	21.09	4.02	0.75	26.06	20.11	5.11	1.03

APPENDIX "B"

1-1/2 Inch Pipe

Date	Run No.	Velocity	Right Inches 16ths	Left Inches 16ths	Difference Inches of Manometer Fluid Inches 16ths	Friction Head Loss Difference × Conversion Factor (0.18158) ft/100 ft	
9-27-66	1	6.90ft/sec	44.06	2.11	41.11	7.57	7% Solids
"	"	"	44.08	2.06	42.02	7.65	
"	"	"	44.09	2.06	42.03	7.66	
"	"	"	44.03	3.03	41.00	7.44	
"	"	"	44.15	2.06	42.09	7.73	
"	"	"	44.10	2.00	42.10	7.74	
"	3	5.73ft/sec	44.05	2.13	41.08	7.54	
"	"	"	44.07	2.08	41.15	7.62	
"	"	"	44.07	2.05	42.02	7.65	
"	"	"	44.11	2.09	42.02	7.65	
"	"	"	44.13	2.06	42.07	7.71	
"	"	"	44.11	2.02	42.09	7.73	
"	4	5.60ft/sec	45.02	2.07	42.11	7.75	
"	"	"	45.03	1.13	43.06	7.88	
"	"	"	44.13	2.00	42.13	7.77	
"	"	"	44.12	2.00	42.12	7.76	
"	"	"	45.03	2.62	43.01	7.82	
"	"	"	45.00	2.06	42.10	7.74	
"	"	"	44.10	2.07	42.03	7.66	
"	"	"	44.09	2.05	42.04	7.67	
"	9	2.08ft/sec	28.07	19.02	9.05	1.69	
"	"	"	28.03	18.12	9.07	1.71	
"	"	"	28.05	18.11	9.10	1.75	
"	"	"	28.05	18.11	9.10	1.75	
"	"	"	28.01	19.01	9.00	1.63	
"	"	"	28.02	19.01	9.01	1.65	
"	"	"	28.08	18.11	9.13	1.78	
"	"	"	28.08	18.10	9.14	1.79	
"	10	3.39ft/sec	34.13	12.13	22.00	3.99	
"	"	"	34.11	12.06	22.05	4.05	
"	"	"	34.06	12.09	21.13	3.96	
"	"	"	34.06	12.10	21.12	3.94	
"	"	"	33.13	13.08	20.05	3.68	
"	"	"	33.13	13.08	20.05	3.68	
"	"	"	33.15	13.05	20.10	3.74	
"	"	"	33.13	13.04	20.09	3.73	
"	11	4.17ft/sec	38.13	8.15	29.14	5.42	
"	"	"	38.11	8.06	30.05	5.50	
"	"	"	38.07	8.08	29.15	5.43	
"	"	"	38.08	8.08	30.00	5.44	
"	"	"	38.07	8.12	29.11	5.39	

APPENDIX "B"

1-1/2 Inch Pipe

Date	Run No.	Velocity	Right Inches 16ths	Left Inches 16ths	Difference Inches of Manometer Fluid Inches 16ths	Friction Head Loss Difference x Conversion Factor (0.18158) ft/100 ft	
9-27-66	11	4.17ft/sec	38.07	8.15	29.08	5.35	7% Solids
"	"	"	38.04	8.15	29.05	5.32	
"	"	"	38.03	8.13	29.06	5.33	
"	12	1.12ft/sec	25.13	21.08	4.05	0.78	
"	"	"	25.11	21.04	4.07	0.81	
"	"	"	25.12	21.03	4.09	0.83	
"	"	"	25.13	21.03	4.10	0.84	
"	"	"	25.14	21.04	4.10	0.84	
"	"	"	25.15	21.03	4.12	0.86	
"	"	"	25.13	21.06	4.07	0.81	
"	"	"	25.12	21.06	4.06	0.79	
9-26-66	2	6.38ft/sec	44.07	3.01	41.06	7.51	9% Solids
"	"	"	44.05	2.13	41.08	7.54	
"	"	"	44.10	2.03	42.07	7.71	
"	"	"	44.11	2.03	42.08	7.72	
"	"	"	43.14	3.04	40.10	7.38	
"	"	"	44.11	2.09	42.02	7.65	
"	"	"	44.14	2.03	42.11	7.75	
"	"	"	44.10	2.04	42.06	7.69	
"	3	5.86ft/sec	45.03	2.04	42.15	7.80	
"	"	"	44.08	2.11	41.13	7.59	
"	"	"	44.11	2.04	42.07	7.71	
"	"	"	44.10	2.03	42.07	7.71	
"	"	"	43.13	3.07	40.06	7.33	
"	"	"	44.11	2.09	42.02	7.65	
"	"	"	44.13	2.04	42.09	7.73	
"	"	"	44.09	2.04	42.05	7.68	
"	4	5.60ft/sec	45.04	2.02	43.02	7.83	
"	"	"	44.06	2.11	41.11	7.57	
"	"	"	44.09	2.05	42.04	7.67	
"	"	"	44.11	2.04	42.07	7.71	
"	"	"	44.00	3.04	40.12	7.40	
"	"	"	44.12	2.10	42.02	7.65	
"	"	"	44.15	2.04	42.11	7.75	
"	"	"	44.09	2.04	42.05	7.68	
"	5	5.34 ft/sec	45.03	2.03	43.00	7.81	
"	"	"	44.05	2.11	41.10	7.56	
"	"	"	44.09	2.04	42.05	7.68	
"	"	"	44.11	2.04	42.07	7.71	
"	"	"	43.15	3.05	40.10	7.38	
"	"	"	44.11	2.10	42.01	7.64	
"	"	"	44.12	2.07	42.05	7.68	

APPENDIX "B"

1-1/2 Inch Pipe

Date	Run No.	Velocity	Right Inches 16ths	Left Inches 16ths	Difference Inches of Manometer Fluid Inches 16ths	Friction Head Loss Difference x Conversion Factor (0.18158) ft/100 ft	
9-26-66	5	5.34ft/sec	43.11	3.02	40.09	7.37	9% Solids
"	6	4.94ft/sec	45.05	2.02	43.03	7.84	
"	"	"	44.11	2.01	42.10	7.74	
"	"	"	45.03	1.12	43.07	7.89	
"	"	"	44.13	2.02	42.11	7.75	
"	"	"	44.09	2.10	41.15	7.62	
"	"	"	44.07	2.15	41.08	7.54	
"	"	"	44.07	2.10	41.13	7.59	
"	"	"	44.08	2.06	42.02	7.65	
"	7	4.94ft/sec	42.11	4.13	37.14	6.88	
"	"	"	42.10	4.06	38.04	6.95	
"	"	"	42.02	4.12	37.06	6.79	
"	"	"	42.03	4.10	37.09	6.82	
"	"	"	41.12	5.05	36.07	6.62	
"	"	"	41.12	5.09	36.03	6.57	
"	"	"	41.13	5.08	36.05	6.59	
"	"	"	41.13	5.02	36.11	6.66	
"	8	3.78ft/sec	37.03	10.04	26.15	4.89	
"	"	"	37.02	10.00	27.00	4.90	
"	"	"	36.09	10.06	26.03	4.75	
"	"	"	36.08	10.06	26.02	4.74	
"	"	"	36.02	11.04	24.14	4.51	
"	"	"	35.15	11.05	24.10	4.47	
"	"	"	36.09	10.10	25.15	4.71	
"	"	"	36.07	10.10	25.13	4.68	
"	9	3.12ft/sec	32.12	14.12	18.00	3.27	
"	"	"	32.11	14.06	18.05	3.33	
"	"	"	32.02	14.13	17.05	3.14	
"	"	"	32.03	14.12	17.07	3.17	
"	"	"	31.13	15.07	16.06	2.97	
"	"	"	31.13	15.07	16.06	2.97	
"	"	"	32.00	15.02	16.14	3.06	
"	"	"	32.00	15.02	16.14	3.06	
"	10	1.65ft/sec	28.06	19.00	9.06	1.70	
"	"	"	28.03	18.12	9.07	1.71	
"	"	"	28.09	18.08	10.01	1.83	
"	"	"	28.09	18.15	9.10	1.75	
"	"	"	28.12	18.07	10.05	1.87	
"	"	"	28.12	18.07	10.05	1.87	
"	"	"	28.04	19.00	9.04	1.68	
"	"	"	28.03	19.00	9.03	1.67	

APPENDIX "B"

1-1/2 Inch Pipe

Date	Run No.	Velocity	Right Inches 16ths	Left Inches 16ths	Fluid Inches 16ths	Friction Head Loss Difference x Conversion Factor (0.18158) ft/100 ft	
9-26-66	11	0.13ft/sec	25.00	22.06	2.10	0.48	9% Solids
"	"	"	24.13	22.01	2.11	0.49	
"	"	"	24.14	22.02	2.12	0.50	
"	"	"	24.13	22.02	2.11	0.49	
"	"	"	25.05	21.15	3.06	0.61	
"	"	"	25.04	21.15	3.05	0.60	
"	"	"	25.03	22.00	3.03	0.58	
"	"	"	25.02	22.01	3.01	0.56	
9-23-66	1	4.17ft/sec	44.03	3.04	40.15	7.43	13.6% Solids
"	"	"	43.09	3.08	40.01	7.27	
"	"	"	44.08	2.05	42.03	7.66	
"	"	"	44.12	2.03	42.09	7.73	
"	"	"	44.00	3.07	40.09	7.37	
"	"	"	44.13	2.08	42.05	7.68	
"	"	"	44.13	2.03	42.10	7.74	
"	"	"	44.13	1.15	42.14	7.79	
"	2	4.17ft/sec	44.03	3.03	41.00	7.44	
"	"	"	43.08	3.07	41.01	7.46	
"	"	"	44.08	2.06	42.02	7.65	
"	"	"	44.11	2.04	42.07	7.71	
"	"	"	43.15	3.03	40.12	7.40	
"	"	"	44.13	2.08	42.05	7.68	
"	"	"	44.13	2.04	42.09	7.73	
"	"	"	44.13	1.15	42.14	7.79	
"	3	4.17ft/sec	44.09	2.12	41.13	7.59	
"	"	"	43.08	3.08	40.00	7.26	
"	"	"	44.07	2.06	42.01	7.64	
"	"	"	44.11	2.04	42.07	7.71	
"	"	"	43.14	2.05	41.09	7.55	
"	"	"	44.13	2.08	42.05	7.68	
"	"	"	44.11	2.04	42.07	7.71	
"	"	"	44.12	2.00	42.12	7.76	
"	5	3.51ft/sec	39.08	7.14	31.10	5.74	12% Solids
"	"	"	39.06	7.09	31.14	5.29	
"	"	"	39.11	7.02	³22.09	5.91	
"	"	"	39.12	7.02	32.10	5.92	
"	"	"	39.07	7.13	31.10	5.74	
"	"	"	39.05	7.15	31.06	5.70	
"	"	"	38.12	8.06	30.10	5.56	
"	"	"	38.12	8.04	30.08	5.54	

APPENDIX "B"

1-1/2 Inch Pipe

Date	Run No.	Velocity	Right Inches 16ths	Left Inches 16ths	Difference Inches of Manometer Fluid Inches 16ths	Friction Head Loss Difference x Conversion Factor (0.18158) ft/100 ft.	
9-23-66	6	1.82ft/sec	36.11	10.10	26.01	4.73	12% Solids
"	"	"	36.10	10.06	26.05	4.78	
"	"	"	36.06	10.10	25.12	4.68	
"	"	"	36.06	10.10	25.12	4.68	
"	"	"	36.02	11.02	25.00	4.54	
"	"	"	36.02	11.03	24.15	4.53	
"	"	"	35.07	11.09	23.14	4.34	
"	"	"	35.07	11.10	23.13	4.33	
"	7	0.78ft/sec	32.14	14.06	18.08	3.36	
"	"	"	32.14	14.02	18.12	3.40	
"	"	"	32.09	14.05	18.04	3.31	
"	"	"	32.08	14.06	18.02	3.29	
"	"	"	32.04	15.01	17.03	3.12	
"	"	"	32.02	15.01	17.01	3.10	
"	"	"	32.13	16.06	16.07	2.98	
"	"	"	32.13	16.06	16.07	2.98	
"	8	0.41ft/sec	28.04	19.02	9.02	1.66	
"	"	"	28.04	18.11	9.09	1.74	
"	"	"	27.15	19.00	8.15	1.62	
"	"	"	27.11	19.02	8.09	1.55	
"	"	"	29.00	18.04	10.12	1.95	
"	"	"	28.13	18.05	10.08	1.91	
"	"	"	28.08	18.11	9.13	1.78	
"	"	"	28.07	18.11	9.12	1.77	
"	9	0.06ft/sec	25.11	21.08	4.03	0.76	
"	"	"	25.10	21.05	4.05	0.78	
"	"	"	24.14	22.00	2.14	0.52	
"	"	"	24.13	22.02	2.11	0.48	
"	"	"	26.03	21.00	5.03	0.94	
"	"	"	26.00	21.01	4.15	0.90	
"	"	"	26.02	21.00	5.02	0.93	
"	"	"	26.01	21.00	5.01	0.92	

APPENDIX "B"

2-Inch Pipe

Date	Run No.	Velocity	Right Inches 16ths	Left Inches 16ths	Difference Inches of Manometer Fluid Inches 16ths	Friction Head Loss Difference x Conversion Factor (0.18158) ft/100 ft
9-27-66	1	4.19ft/sec	34.04	13.10	20.10	3.75
"	"	"	34.10	13.03	21.07	3.89
"	"	"	33.12	13.02	20.10	3.75
"	"	"	34.00	13.04	20.12	3.77
"	"	"	33.10	13.08	20.02	3.65
"	"	"	34.01	13.14	20.03	3.67
"	"	"	33.05	13.10	19.11	3.57
"	"	"	33.15	13.14	20.01	3.64
"	2	3.79ft/sec	34.02	13.11	20.99	3.73
"	"	"	33.09	13.04	20.05	3.68
"	"	"	33.09	13.04	20.05	3.68
"	"	"	33.13	13.07	20.06	3.70
"	"	"	33.03	13.15	19.04	3.49
"	"	"	33.09	14.05	19.04	3.49
"	"	"	33.03	13.12	19.07	3.52
"	"	"	33.12	14.01	19.11	3.57
"	3	3.48ft/sec	31.12	16.02	15.10	2.84
"	"	"	31.04	15.10	15.10	2.84
"	"	"	31.03	15.11	15.08	2.81
"	"	"	31.07	15.13	15.10	2.84
"	"	"	31.02	16.01	15.01	2.74
"	"	"	31.06	16.06	15.00	2.72
"	"	"	31.01	16.00	15.01	2.74
"	"	"	31.07	16.02	15.05	2.78
"	4	3.40ft/sec	30.15	16.14	14.01	2.55
"	"	"	30.08	16.08	14.00	2.54
"	"	"	30.06	16.08	13.14	2.52
"	"	"	30.09	16.10	13.15	2.53
"	"	"	30.05	16.13	13.08	2.45
"	"	"	30.11	17.01	13.10	2.47
"	"	"	30.05	16.13	13.08	2.45
"	"	"	30.10	16.15	13.11	2.49

7% Solids

APPENDIX "B"

2-Inch Pipe

Date	Run No.	Velocity	Right Inches 16ths	Left Inches 16ths	Difference Inches of Manometer Fluid Inches 16ths	Friction Head Loss Difference x Conversion Factor (0.18158) ft/100 ft	
9-27-67	9	1.26ft/sec	26.14	20.11	6.03	1.12	7% Solids
"	"	"	26.10	20.09	6.03	1.12	
"	"	"	26.07	20.07	6.00	1.09	
"	"	"	26.11	20.08	6.03	1.12	
"	"	"	27.06	19.11	7.11	1.40	
"	"	"	27.09	19.15	7.10	1.38	
"	"	"	26.12	19.10	7.02	1.29	
"	"	"	27.13	19.10	7.03	1.31	
"	10	2.06ft/sec	27.06	20.03	7.03	1.30	
"	"	"	27.03	20.01	7.02	1.29	
"	"	"	26.13	20.04	6.09	1.19	
"	"	"	26.15	20.06	6.09	1.19	
"	"	"	27.04	19.13	7.07	1.35	
"	"	"	27.09	20.00	7.09	1.37	
"	"	"	27.06	20.00	7.06	1.33	
"	"	"	27.08	20.01	7.07	1.35	
"	11	2.53ft/sec	28.12	18.14	9.14	1.80	
"	"	"	28.07	18.10	9.13	1.78	
"	"	"	28.04	18.13	9.07	1.71	
"	"	"	28.06	18.15	9.07	1.71	
"	"	"	28.05	18.12	9.09	1.73	
"	"	"	28.09	19.01	9.08	1.72	
"	"	"	28.07	18.14	9.09	1.73	
"	"	"	28.11	18.14	9.13	1.78	
"	12	0.68ft/sec	25.06	22.02	3.04	0.59	
"	"	"	25.03	22.01	3.02	0.57	
"	"	"	25.01	22.03	2.14	0.52	
"	"	"	25.01	22.02	2.15	0.53	
"	"	"	25.04	21.13	3.07	0.63	
"	"	"	25.08	21.15	3.09	0.65	
"	"	"	25.07	22.00	3.07	0.63	
"	"	"	25.07	21.15	3.08	0.64	

APPENDIX "B"

2-Inch Pipe

Date	Run No.	Velocity	Right Inches 16ths	Left Inches 16ths	Difference Inches of Manometer Fluid Inches 16ths	Friction Head Loss Difference x Conversion Factor (0.18158) ft/100 ft
9-26-66	1	4.03ft/sec	33.10	14.05	19.05	3.50
"	"	"	33.00	13.12	19.04	3.49
"	"	"	33.02	13.12	19.06	3.51
"	"	"	33.05	13.15	19.06	3.51
"	"	"	32.14	14.04	18.10	3.38
"	"	"	33.02	14.09	18.09	3.37
"	"	"	33.02	13.15	19.03	3.48
"	"	"	33.10	14.05	19.05	3.50
"	2	3.87ft/sec	35.07	12.08	22.15	4.16
"	"	"	34.10	12.00	22.10	4.11
"	"	"	34.12	12.00	22.12	4.13
"	"	"	34.15	12.04	22.11	4.12
"	"	"	34.03	13.00	21.03	3.85
"	"	"	34.11	13.06	21.05	3.87
"	"	"	34.00	12.14	21.02	3.84
"	"	"	34.11	13.04	21.07	3.89
"	3	3.56ft/sec	34.00	13.15	20.01	3.64
"	"	"	33.05	13.06	19.15	3.62
"	"	"	33.05	13.08	19.13	3.60
"	"	"	33.07	13.11	19.12	3.59
"	"	"	33.05	13.05	20.00	3.63
"	"	"	32.15	14.02	18.13	3.42
"	"	"	33.03	13.13	19.06	3.52
"	"	"	33.12	14.03	19.09	3.55
"	4	3.40ft/sec	31.11	16.00	15.11	2.85
"	"	"	31.04	15.10	15.10	2.84
"	"	"	31.06	15.10	15.12	2.86
"	"	"	31.08	15.12	15.12	2.86
"	"	"	31.02	16.02	15.00	2.72
"	"	"	31.08	16.06	15.02	2.75
"	"	"	31.02	16.00	15.02	2.75
"	"	"	31.04	16.09	14.11	2.67

9% Solids

APPENDIX "B"

2-Inch Pipe

Date	Run No.	Velocity	Right Inches 16ths	Left Inches 16ths	Difference Inches of Manometer Fluid Inches 16ths	Friction Head Loss Difference x Conversion Factor (0.18158) ft/100 ft	
9-26-66	5	3.24ft/sec	31.06	16.07	14.15	2.71	9% Solids
"	"	"	30.14	16.01	14.13	2.69	
"	"	"	30.13	16.02	14.11	2.67	
"	"	"	31.00	16.04	13.12	2.50	
"	"	"	30.14	16.04	14.10	2.66	
"	"	"	31.01	16.12	14.05	2.60	
"	"	"	27.14	19.06	8.08	1.54	
"	"	"	31.07	16.05	15.02	2.75	
"	6	3.00ft/sec	31.09	16.02	15.07	2.80	
"	"	"	31.01	15.12	15.05	2.78	
"	"	"	31.01	15.12	15.05	2.78	
"	"	"	31.04	15.15	15.05	2.81	
"	"	"	30.11	16.06	14.05	2.60	
"	"	"	31.01	16.11	14.06	2.61	
"	"	"	30.06	16.12	13.10	2.47	
"	"	"	30.15	16.13	14.02	2.56	
"	7	3.00ft/sec	29.12	17.13	11.15	2.17	
"	"	"	29.08	17.06	12.02	2.20	
"	"	"	29.10	17.05	12.05	2.24	
"	"	"	29.13	17.07	12.06	2.25	
"	"	"	29.11	17.06	12.05	2.24	
"	"	"	22.05	24.15	-2.10	-0.48	
"	"	"	29.14	17.03	12.11	2.30	
"	"	"	27.10	10.08	17.02	3.11	
"	8	2.29ft/sec	29.09	18.02	11.07	2.07	
"	"	"	29.05	17.12	11.09	2.09	
"	"	"	29.01	17.15	11.02	2.02	
"	"	"	29.03	18.00	11.03	2.03	
"	"	"	29.05	17.12	11.09	2.09	
"	"	"	29.10	18.00	11.10	2.11	
"	"	"	29.00	18.03	10.13	1.96	
"	"	"	29.01	18.08	10.09	1.91	

APPENDIX "B"

2-Inch Pipe

Date	Run No.	Velocity	Right Inches 16ths	Left Inches 16ths	Difference Inches of Manometer Fluid Inches 16ths	Friction Head Loss = Difference x Conversion Factor (0.18158) ft/100 ft	
9-26-66	9	1.90ft/sec	28.04	19.04	9.00	1.63	9% Solids
"	"	"	28.00	19.00	9.00	1.63	
"	"	"	28.01	18.14	9.03	1.67	
"	"	"	28.04	19.00	9.04	1.67	
"	"	"	28.10	18.06	10.04	1.86	
"	"	"	29.00	18.08	10.08	1.91	
"	"	"	28.09	18.10	9.15	1.80	
"	"	"	28.11	18.14	9.13	1.78	
"	10	1.00ft/sec	26.15	20.08	6.07	1.17	
"	"	"	26.14	20.05	6.09	1.19	
"	"	"	27.09	19.09	8.00	1.45	
"	"	"	27.09	19.09	8.00	1.45	
"	"	"	28.05	18.12	9.09	1.74	
"	"	"	28.10	18.15	9.11	1.76	
"	"	"	27.07	19.13	7.10	1.38	
"	"	"	27.08	19.15	7.09	1.37	
"	11	0.08ft/sec	25.01	22.04	2.13	0.51	
"	"	"	25.01	22.04	2.13	0.51	
"	"	"	25.04	21.15	3.05	0.60	
"	"	"	25.04	21.15	3.05	0.60	
"	"	"	25.06	21.12	3.10	0.66	
"	"	"	25.09	21.15	3.10	0.66	
"	"	"	25.14	21.07	4.07	0.81	
"	"	"	26.01	21.07	4.10	0.84	
9-23-66	1	2.53ft/sec	38.07	9.09	28.14	5.24	13.6% Solids
"	"	"	37.06	8.08	28.14	5.24	
"	"	"	38.03	8.04	29.15	5.44	
"	"	"	38.11	8.07	30.04	5.49	
"	"	"	38.06	8.12	29.10	5.38	
"	"	"	38.15	9.03	29.12	5.40	
"	"	"	37.10	8.12	28.14	5.24	
"	"	"	38.12	9.07	29.05	5.32	

APPENDIX "C"

Terminal Facility Costs

APPENDIX "C"

TERMINAL FACILITY COSTS

Population:	125 Thousand	250 Thousand	500 Thousa
Tons dry solids per year	2,600	5,200	10,400
Acres of 25% Solids Sludge Cake (2-inch depth) per year	45	93	186
Tons dry per acre. (56.4 tons dry solids = 2-inch 25% Cake)	57.8	55.9	55.9
Seeding & Planting Costs			
Dollars per Dry Ton	$ .35	$ .36	$ .36
Dollars per year	$ 900.00	$ 1,860.00	$ 3,720.00
Labor & Equipment Costs			
A. Tractor equipped with backhoe @ $11,000 with 10 yr. depreciation	1,100.00	1,100.00	1,100.00
B. Hydroseeder 1500 gal. capacity @ $5,500 with 10 yr. depreciation	-	-	-
C. Sheds, Pumps, Signs, Tools, Supplies, Pipe, etc.	2,900.00	2,900.00	3,400.00
D. Manpower - Fulltime			
5-Day week @ $6500/yr/man	13,000.00	13,000.00	13,000.00
7-Day week @ $9700/yr/man	-	-	-
Total Terminal Facility Cost (Dollars per Year)	$ 17,900.00	$18,860.00	$21,220.00
Dollars per Dry Ton	$6.89	$3.36	$2.04
Dollars per Acre	$398.00	$203.00	$114.00

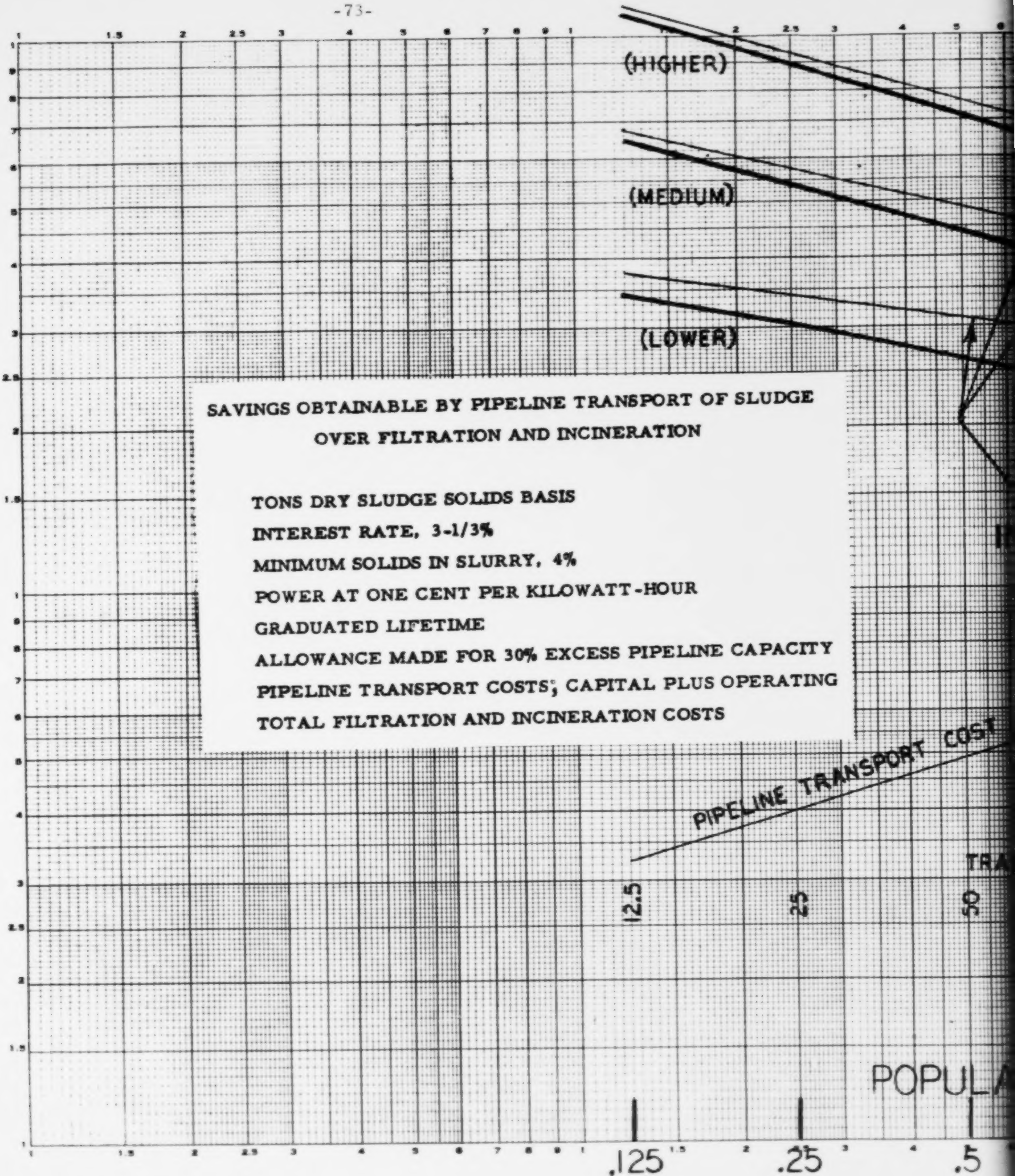
APPENDIX "C"

INAL FACILITY COSTS

ousand	250 Thousand	500 Thousand	1 Million	2 Million	4 Million
00	5,200	10,400	20,800	41,600	83,200
45	93	186	372	744	1,500
.8	55.9	55.9	55.9	55.9	55.6
5	$ .36	$ .36	$ .36	$ .36	$ .36
.00	$ 1,860.00	$ 3,720.00	$ 7,440.00	$ 14,880.00	$30,000.00
.00	1,100.00	1,100.00	2,200.00	2,200.00	5,500.00
	-	-	-	550.00	550.00
.00	2,900.00	3,400.00	3,900.00	4,650.00	9,750.00
0.00	13,000.00	13,000.00	-	-	-
-	-	-	19,400.00	29,100.00	58,200.00
.00	$18,860.00	$21,220.00	$33,940.00	$52,380.00	$104,000.00
9	$3.36	$2.04	$1.63	$1.26	$1.25
0	$203.00	$114.00	$91.00	$70.00	$69.00

APPENDIX "D"

Savings



SAVINGS OBTAINABLE BY PIPELINE TRANSPORT OF SLUDGE OVER FILTRATION AND INCINERATION

TONS DRY SLUDGE SOLIDS BASIS
INTEREST RATE, 3-1/3%
MINIMUM SOLIDS IN SLURRY, 4%
POWER AT ONE CENT PER KILOWATT-HOUR
GRADUATED LIFETIME
ALLOWANCE MADE FOR 30% EXCESS PIPELINE CAPACITY
PIPELINE TRANSPORT COSTS, CAPITAL PLUS OPERATING
TOTAL FILTRATION AND INCINERATION COSTS

A

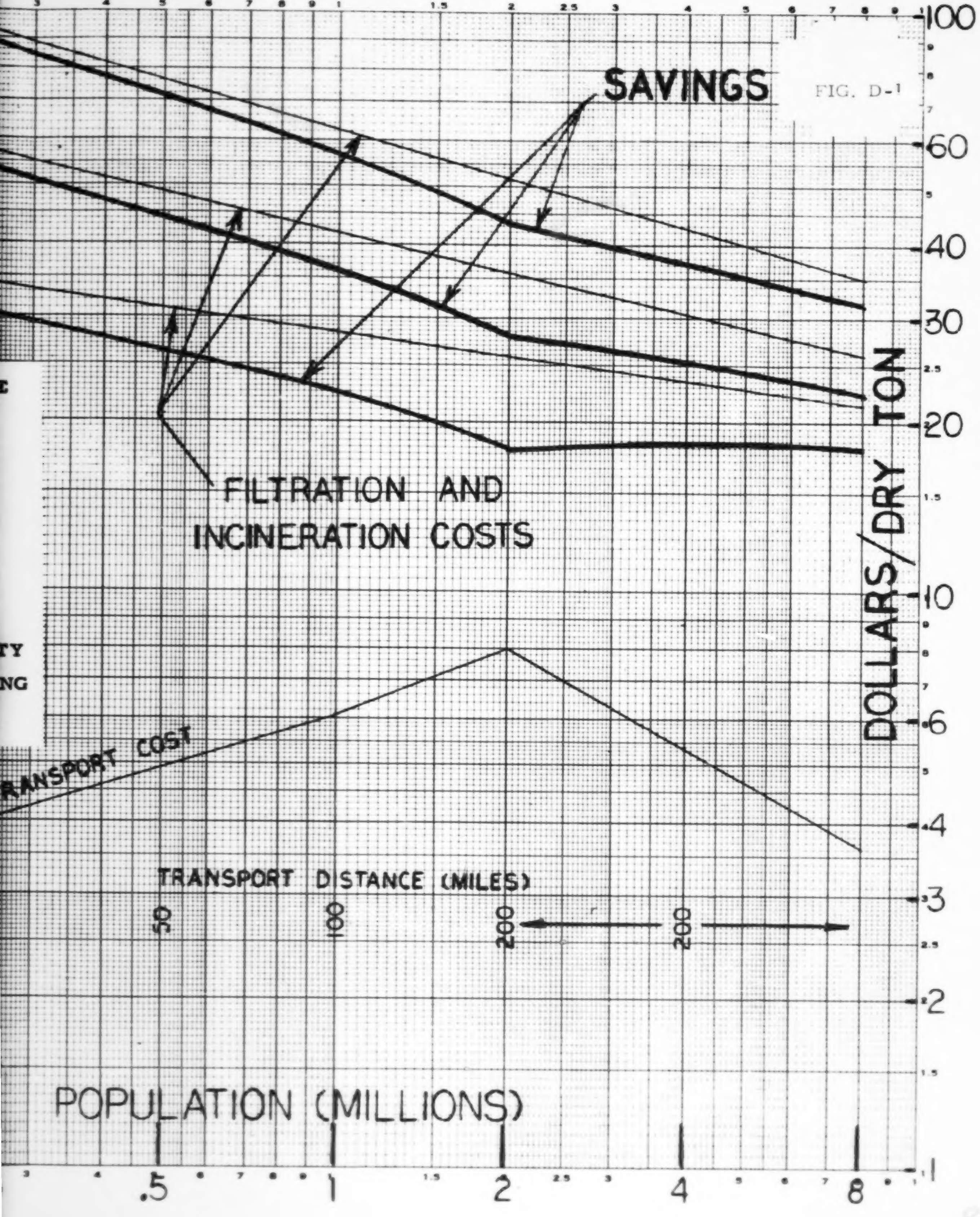
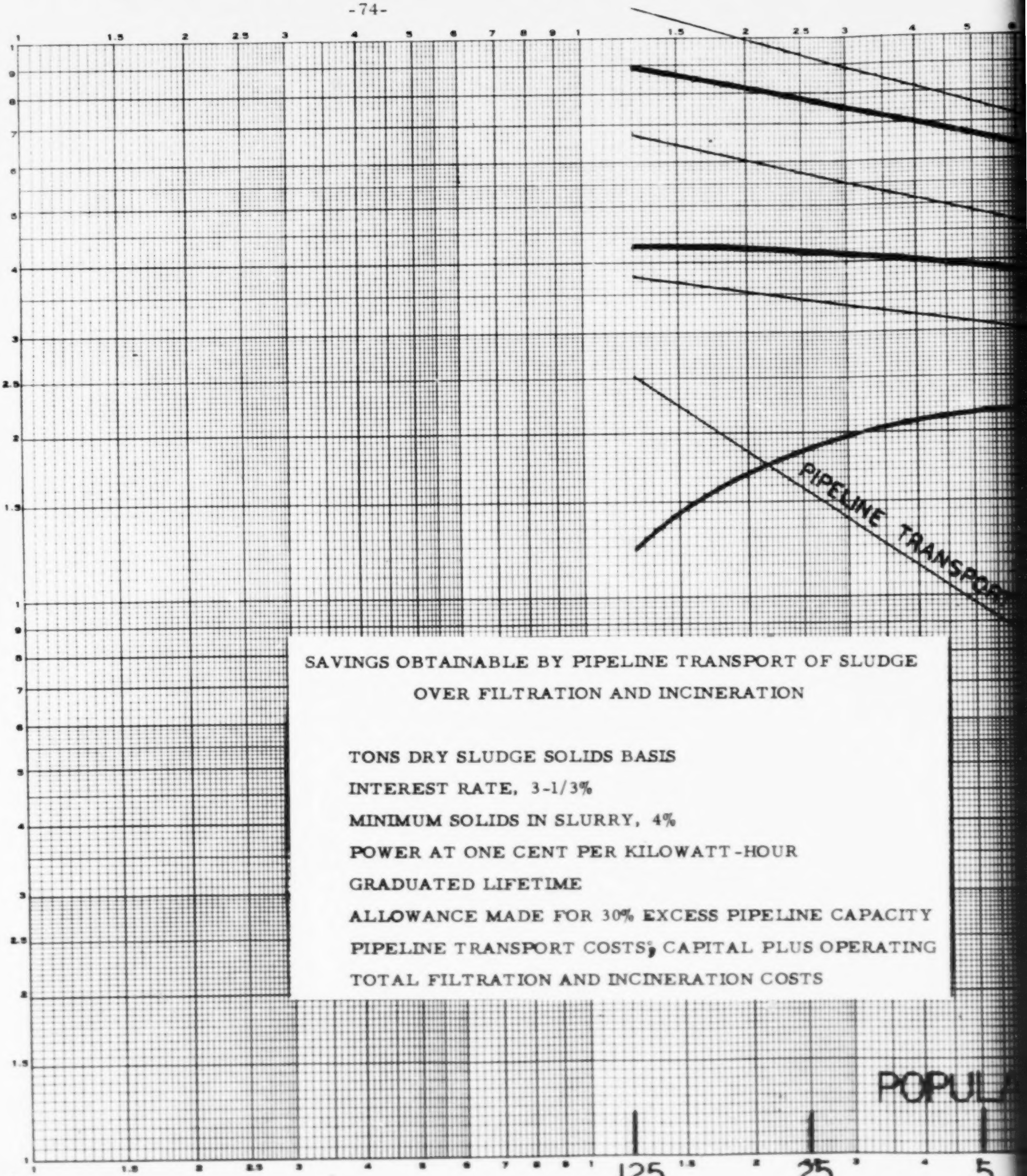


FIG. D-1

SAVINGS
FILTRATION AND INCINERATION COSTS
RANSPORT COST
TRANSPORT DISTANCE (MILES)
50
100
200
200
POPULATION (MILLIONS)
.5
1
2
4
8
DOLLARS/DRY TON
100
60
40
30
20
10
6
4
3
2
1
E
TY
NG



SAVINGS OBTAINABLE BY PIPELINE TRANSPORT OF SLUDGE OVER FILTRATION AND INCINERATION

TONS DRY SLUDGE SOLIDS BASIS
INTEREST RATE, 3-1/3%
MINIMUM SOLIDS IN SLURRY, 4%
POWER AT ONE CENT PER KILOWATT-HOUR
GRADUATED LIFETIME
ALLOWANCE MADE FOR 30% EXCESS PIPELINE CAPACITY
PIPELINE TRANSPORT COSTS, CAPITAL PLUS OPERATING
TOTAL FILTRATION AND INCINERATION COSTS

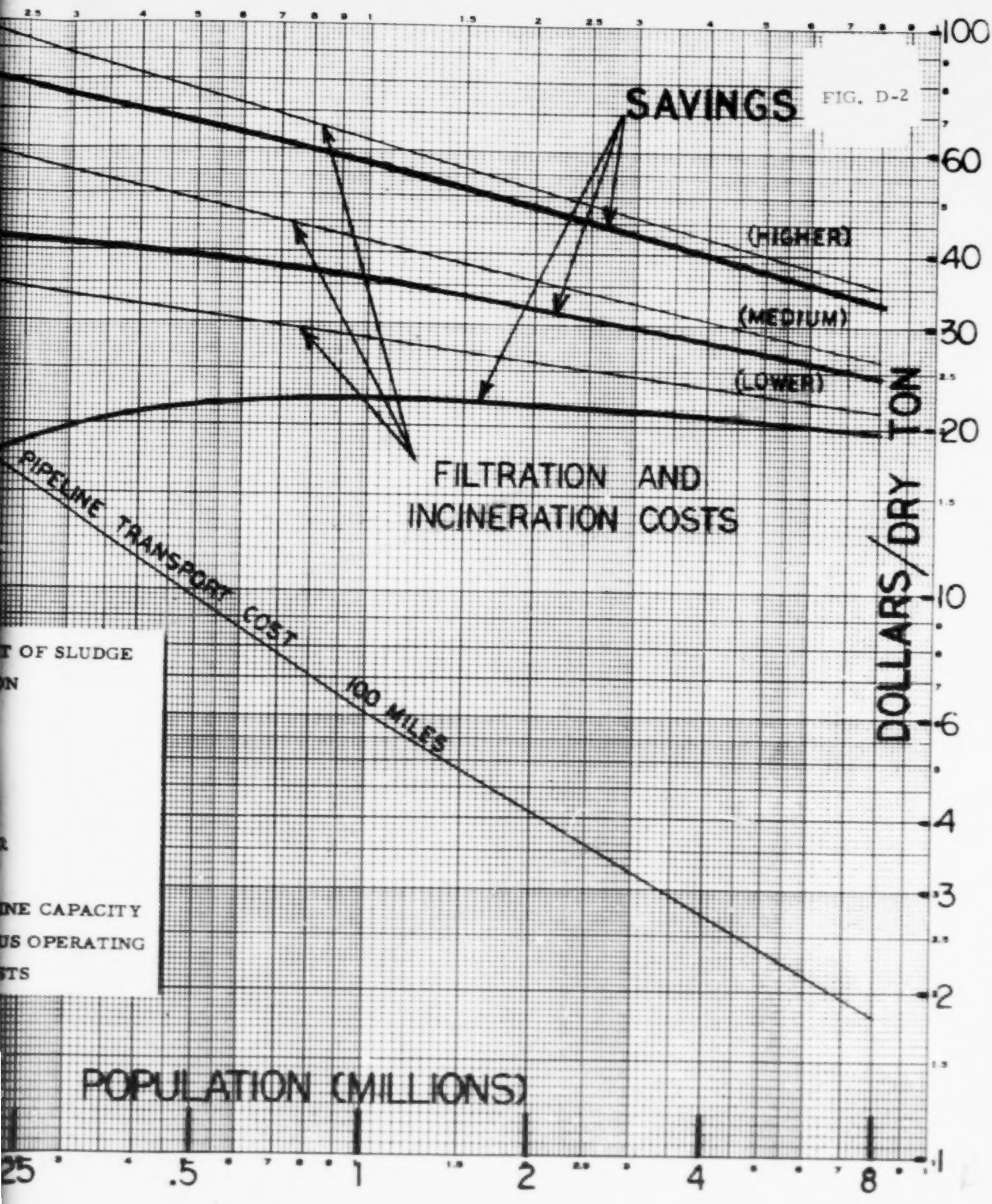
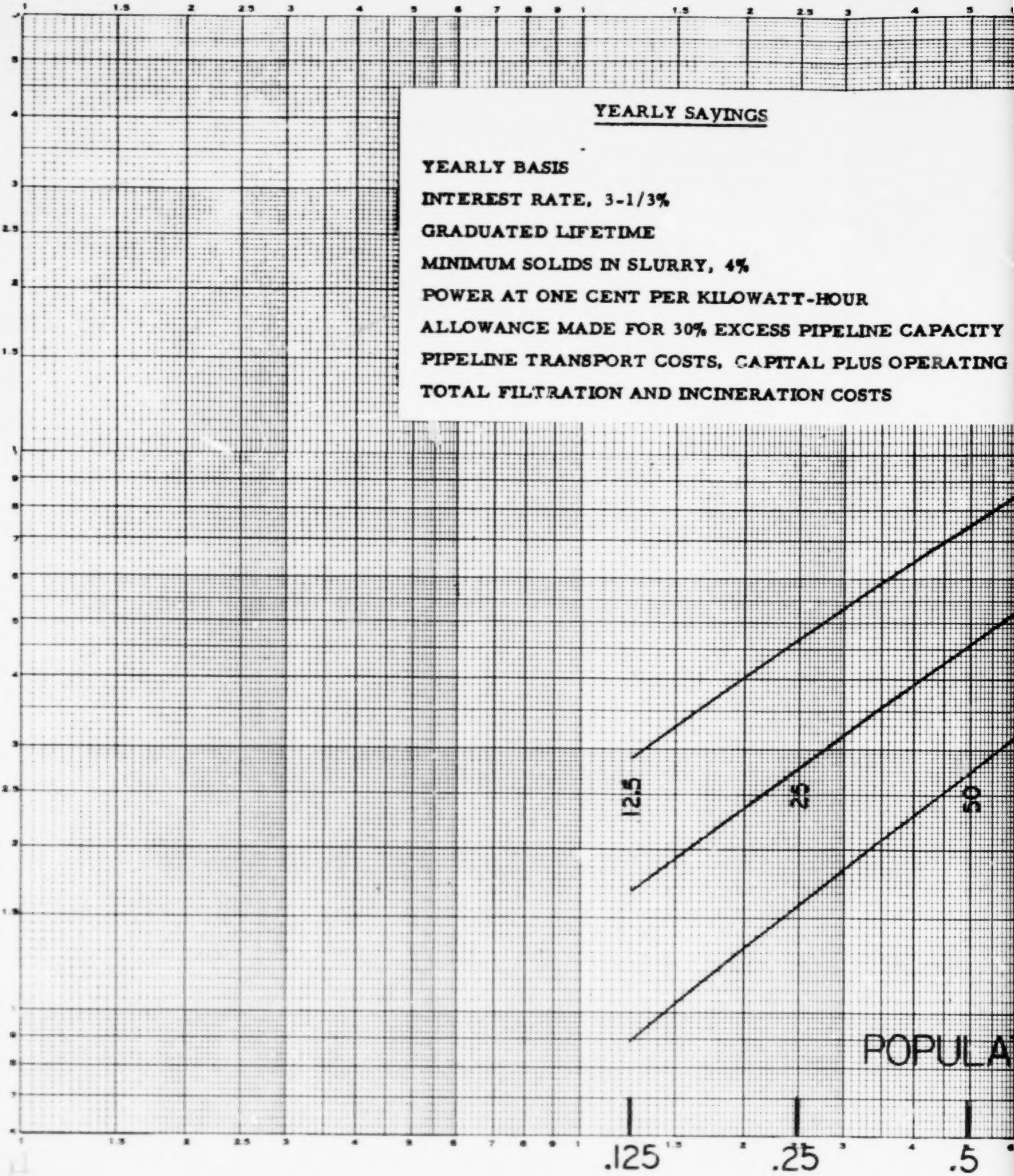

SAVINGS
(HIGHER)
(MEDIUM)
(LOWER)
FILTRATION AND INCINERATION COSTS
PIPELINE TRANSPORT COST
100 MILES
DOLLARS/DRY TON
POPULATION (MILLIONS)
100
60
40
30
20
10
6
4
3
2
1
25
.5
1
2
4
8
T OF SLUDGE
ON
R
INE CAPACITY
US OPERATING
STS

FIG. D-2



YEARLY SAVINGS

YEARLY BASIS

INTEREST RATE, 3-1/3%

GRADUATED LIFETIME

MINIMUM SOLIDS IN SLURRY, 4%

POWER AT ONE CENT PER KILOWATT-HOUR

ALLOWANCE MADE FOR 30% EXCESS PIPELINE CAPACITY

PIPELINE TRANSPORT COSTS, CAPITAL PLUS OPERATING

TOTAL FILTRATION AND INCINERATION COSTS

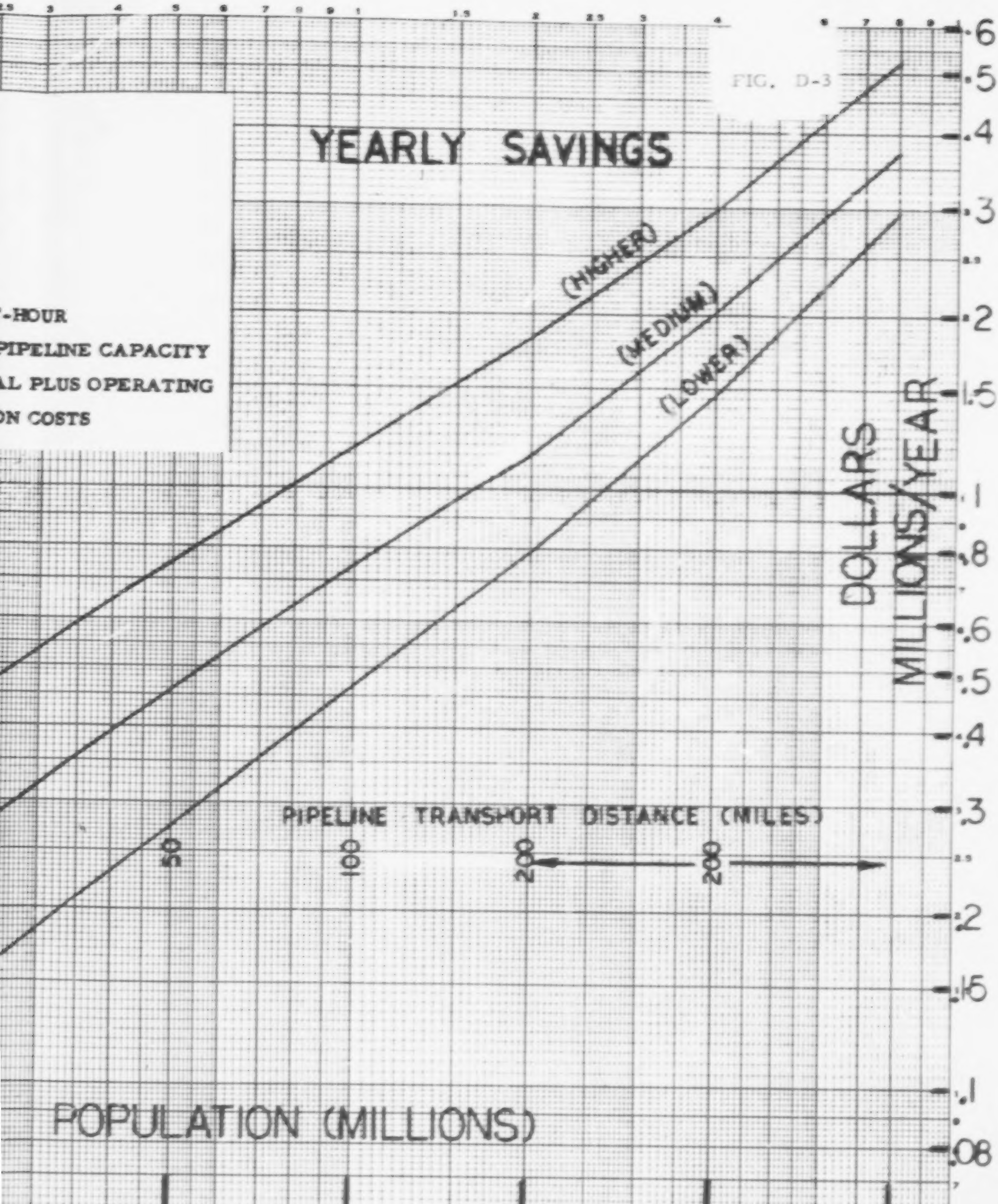
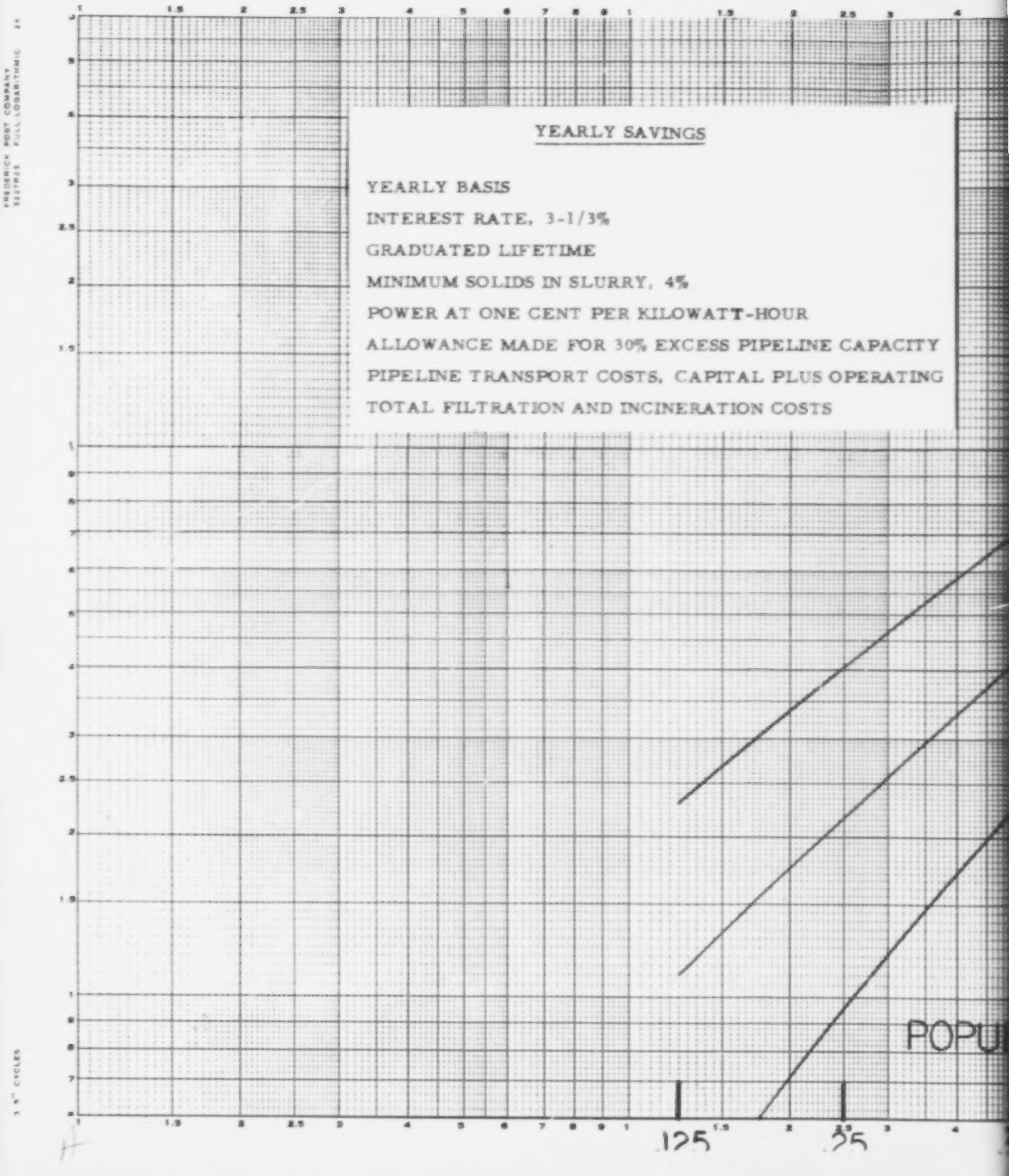


FIG. D-3

YEARLY SAVINGS
-HOUR
PIPELINE CAPACITY
AL PLUS OPERATING
ON COSTS
(HIGHER)
(MEDIUM)
(LOWER)
PIPELINE TRANSPORT DISTANCE (MILES)
50
100
200
200
DOLLARS
MILLIONS/YEAR
.6
.5
.4
.3
.2
1.5
1
.8
.6
.5
.4
.3
.2
.15
.1
.08
POPULATION (MILLIONS)
.5
1
2
4
8



YEARLY SAVINGS

YEARLY BASIS

INTEREST RATE, 3-1/3%

GRADUATED LIFETIME

MINIMUM SOLIDS IN SLURRY, 4%

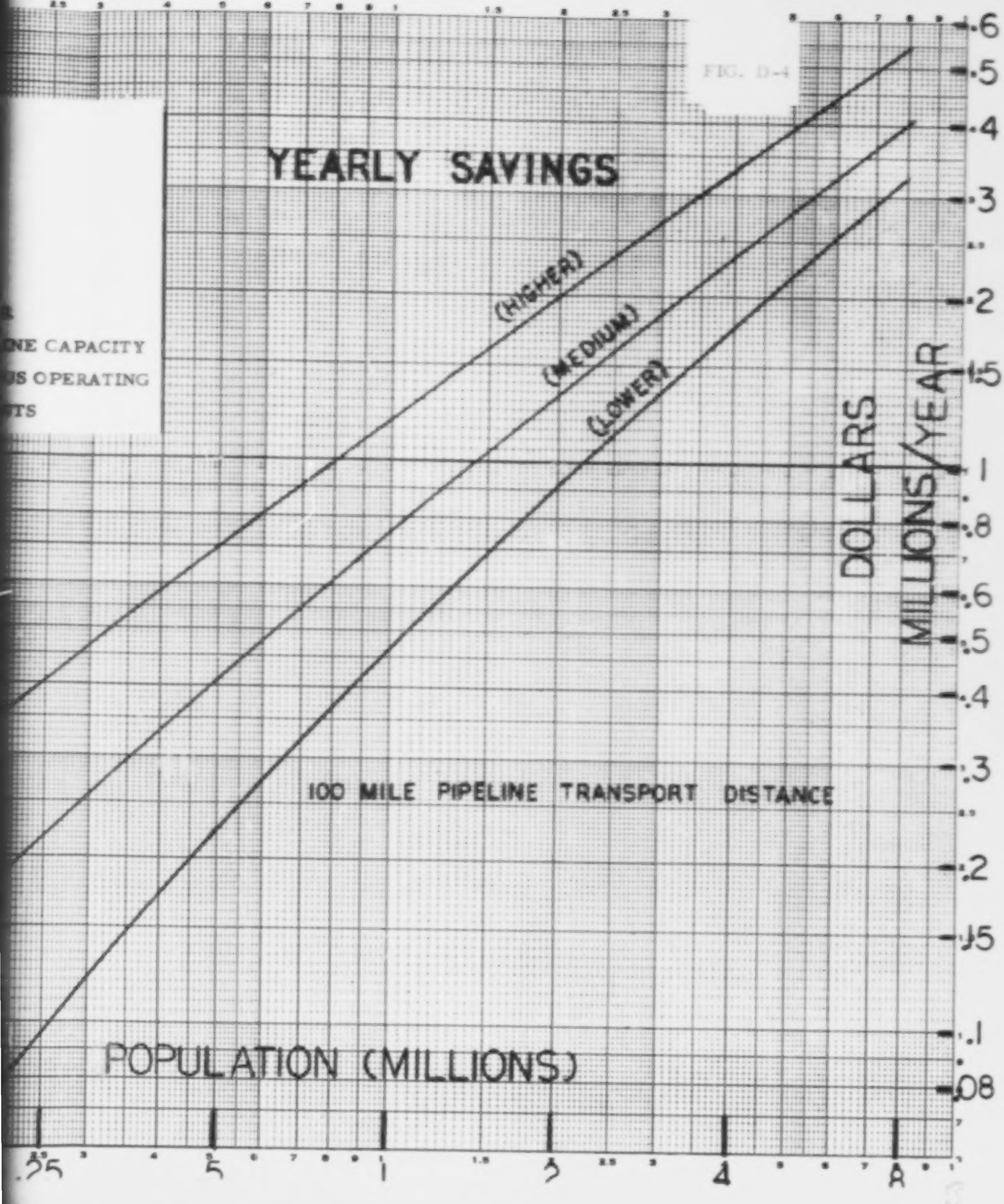
POWER AT ONE CENT PER KILOWATT-HOUR

ALLOWANCE MADE FOR 30% EXCESS PIPELINE CAPACITY

PIPELINE TRANSPORT COSTS, CAPITAL PLUS OPERATING

TOTAL FILTRATION AND INCINERATION COSTS

FIG. D-4



R
NE CAPACITY
US OPERATING
TS

APPENDIX "E"

Cost Estimation

AVERAGE TOTAL ANNUAL CAPITAL PLUS POWER TRANSPORT, AND VARIANCE AS FUNCTION OF PE FOR 4, 5, AND 6% IN BEST PIPE DIAMETER AT 3-1 AMORTIZATION.

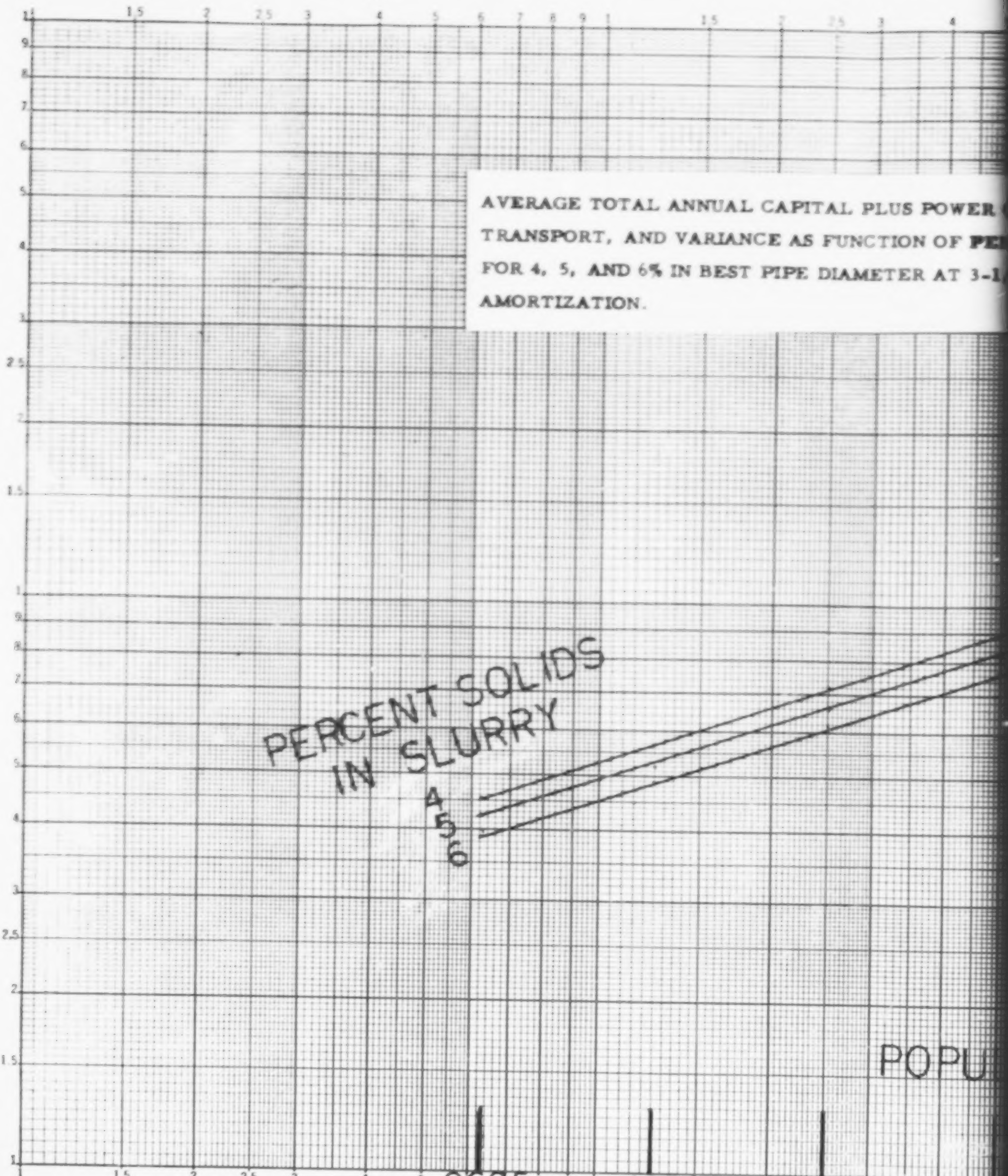
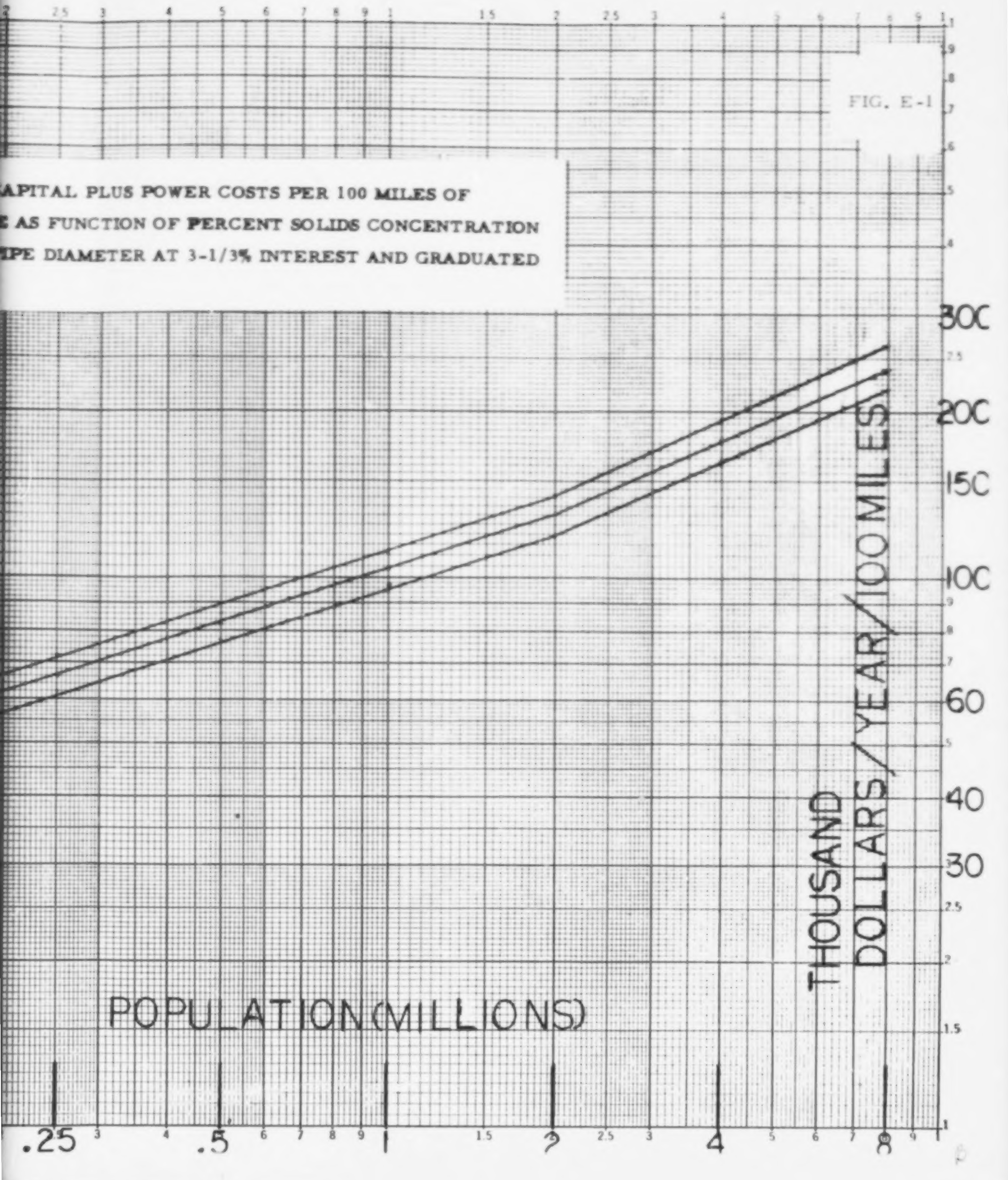
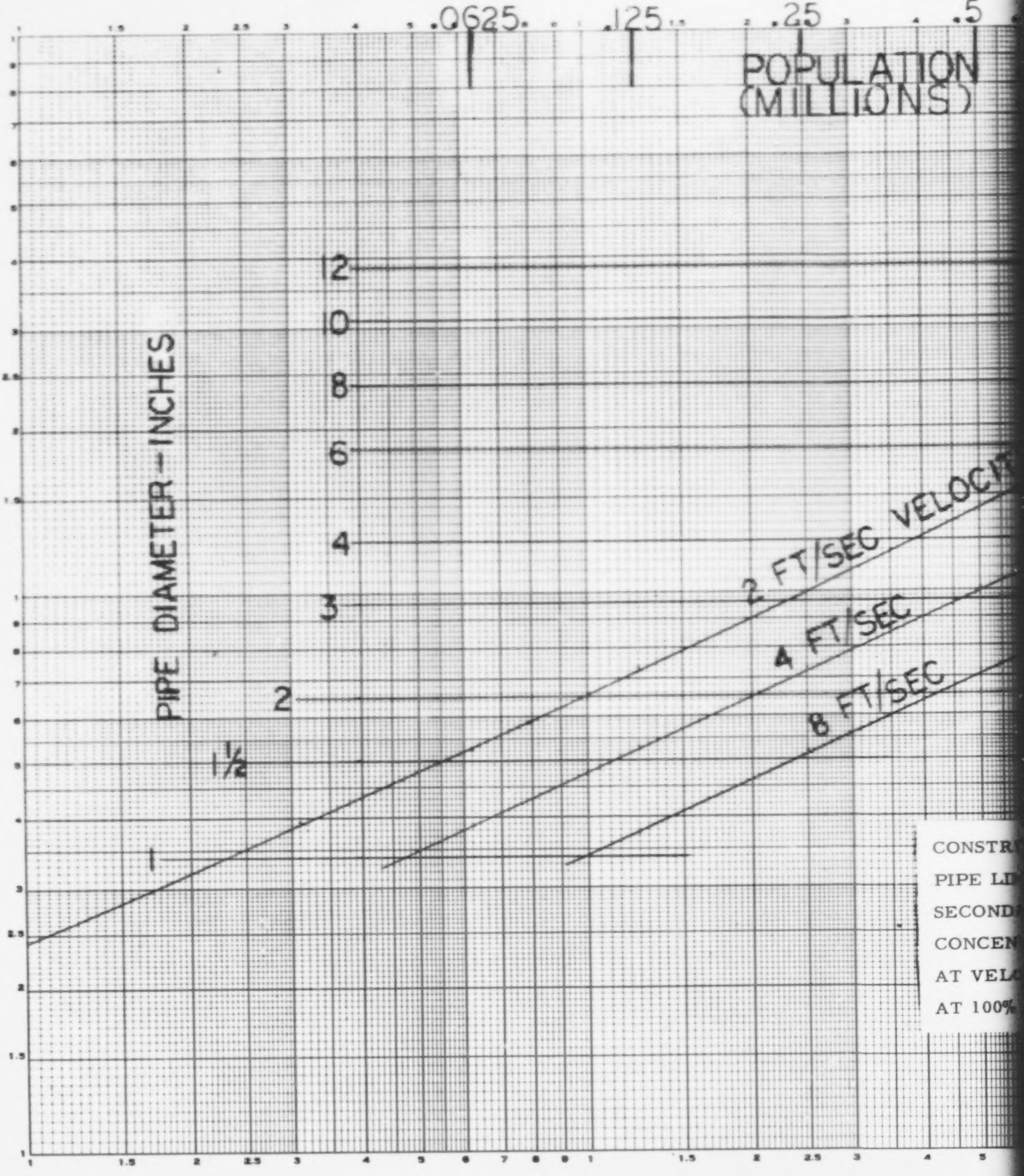


FIG. E-1

APITAL PLUS POWER COSTS PER 100 MILES OF
E AS FUNCTION OF PERCENT SOLIDS CONCENTRATION
IPE DIAMETER AT 3-1/3% INTEREST AND GRADUATED




.0625
.125
.25
.5
POPULATION (MILLIONS)
PIPE DIAMETER – INCHES
12
10
8
6
4
3
2
1½
1
2 FT/SEC VELOCIT
4 FT/SEC
8 FT/SEC
CONSTR
PIPE LI
SECOND
CONCEN
AT VEL
AT 100%

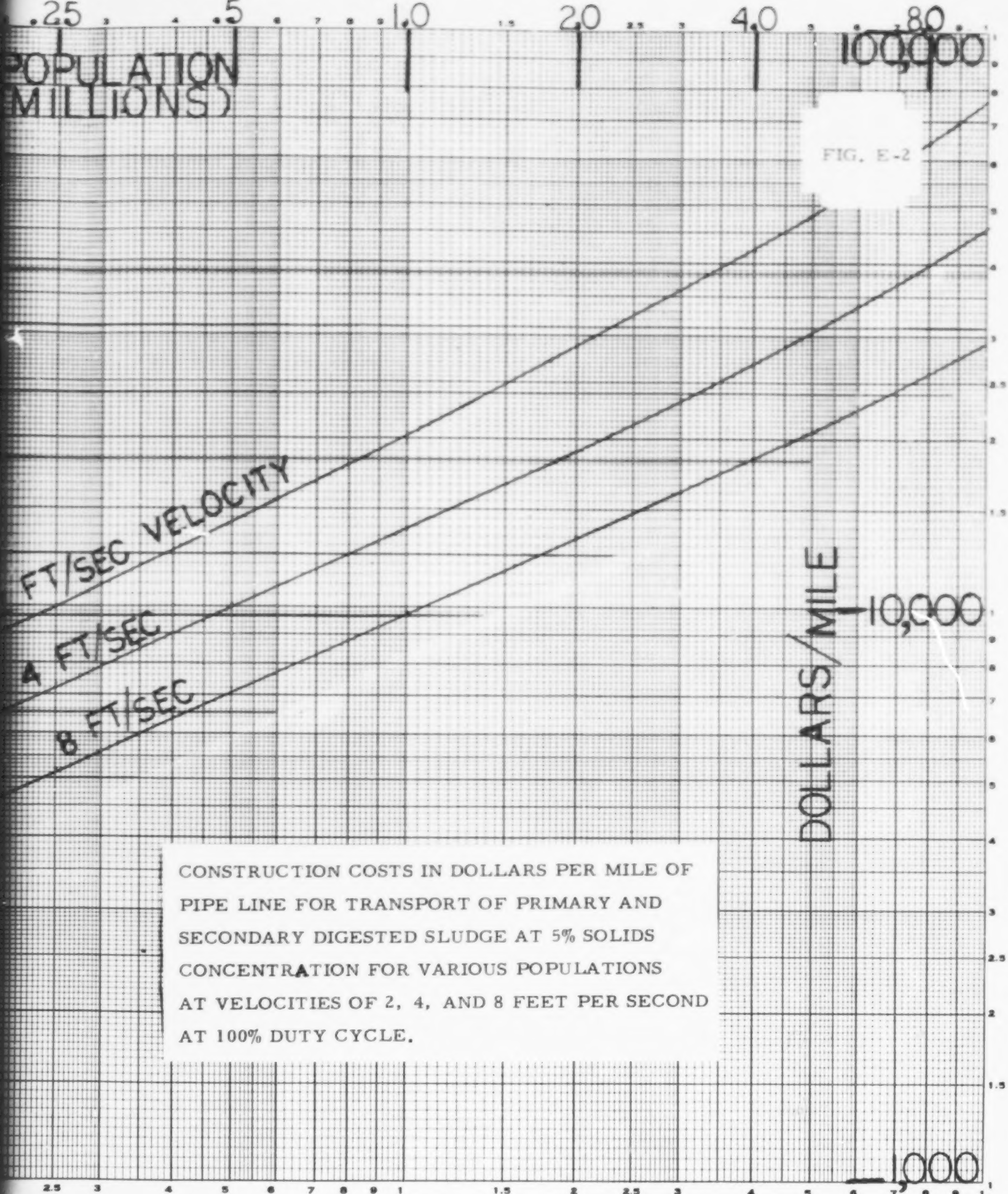
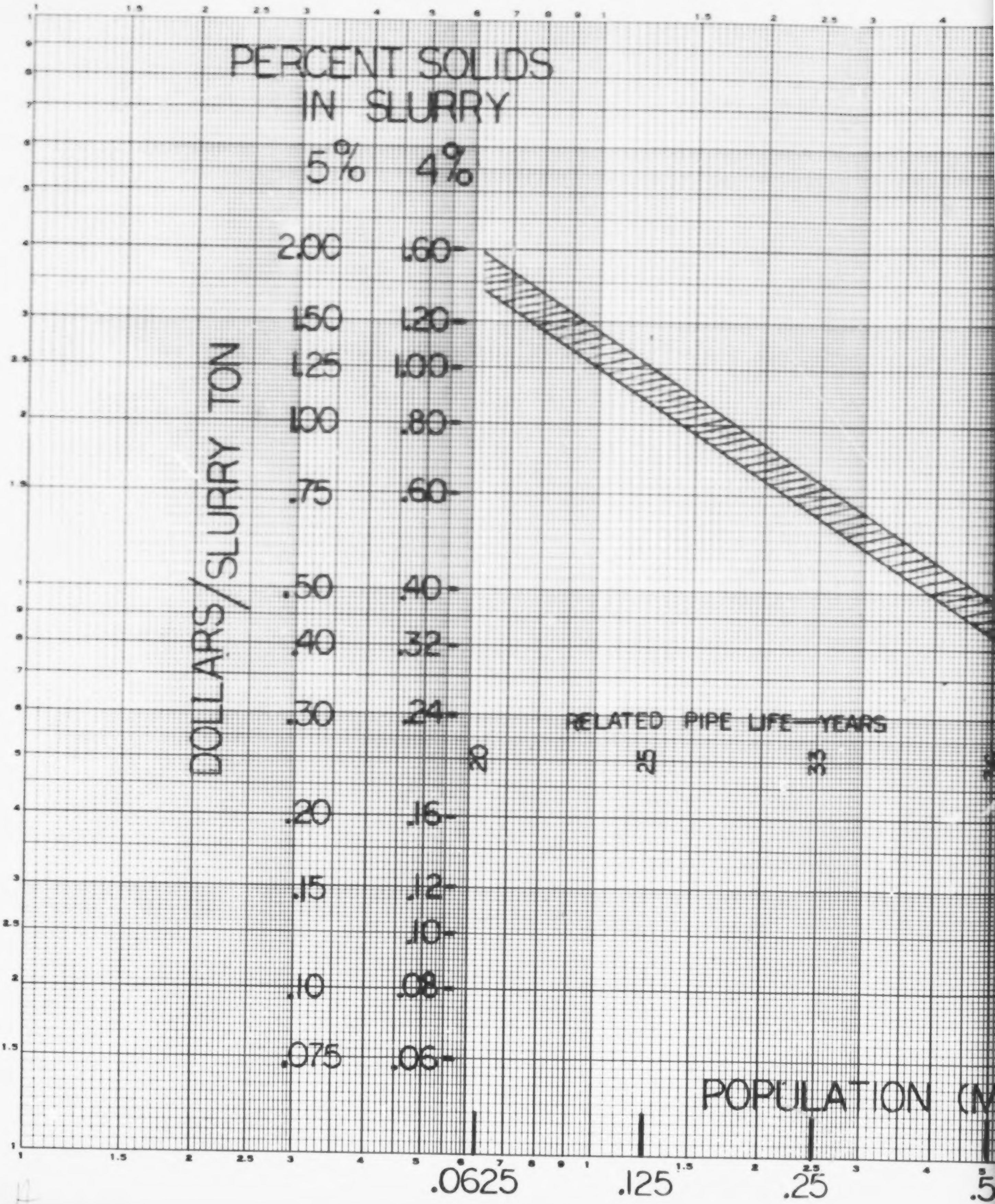


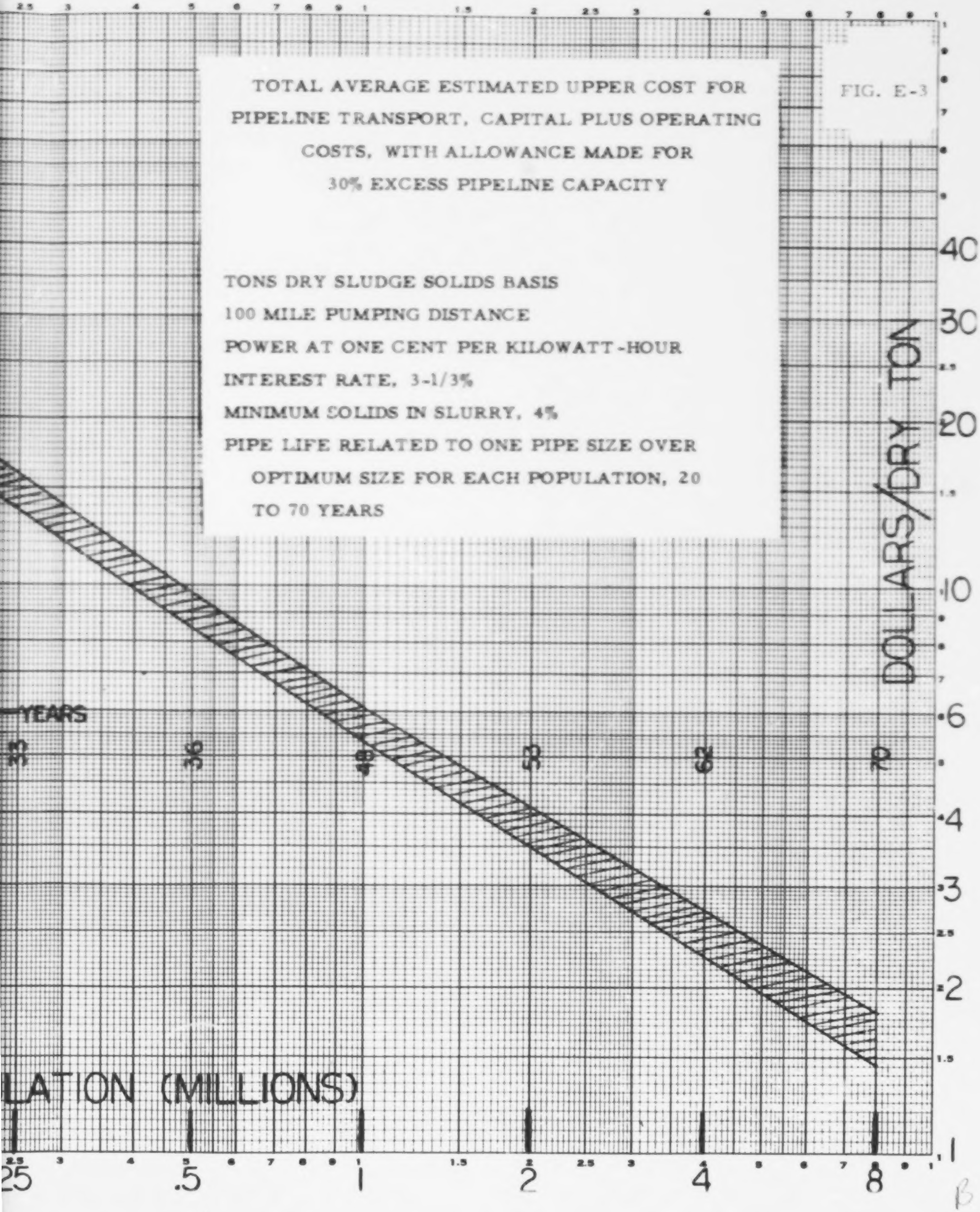
FIG. E-2

CONSTRUCTION COSTS IN DOLLARS PER MILE OF PIPE LINE FOR TRANSPORT OF PRIMARY AND SECONDARY DIGESTED SLUDGE AT 5% SOLIDS CONCENTRATION FOR VARIOUS POPULATIONS AT VELOCITIES OF 2, 4, AND 8 FEET PER SECOND AT 100% DUTY CYCLE.



FREDERICK POST COMPANY 322TR23 FULL-LOGARITHMIC 2x3 5" CYCLES

FIG. E-3


TOTAL AVERAGE ESTIMATED UPPER COST FOR PIPELINE TRANSPORT, CAPITAL PLUS OPERATING COSTS, WITH ALLOWANCE MADE FOR 30% EXCESS PIPELINE CAPACITY

TONS DRY SLUDGE SOLIDS BASIS

100 MILE PUMPING DISTANCE

POWER AT ONE CENT PER KILOWATT-HOUR

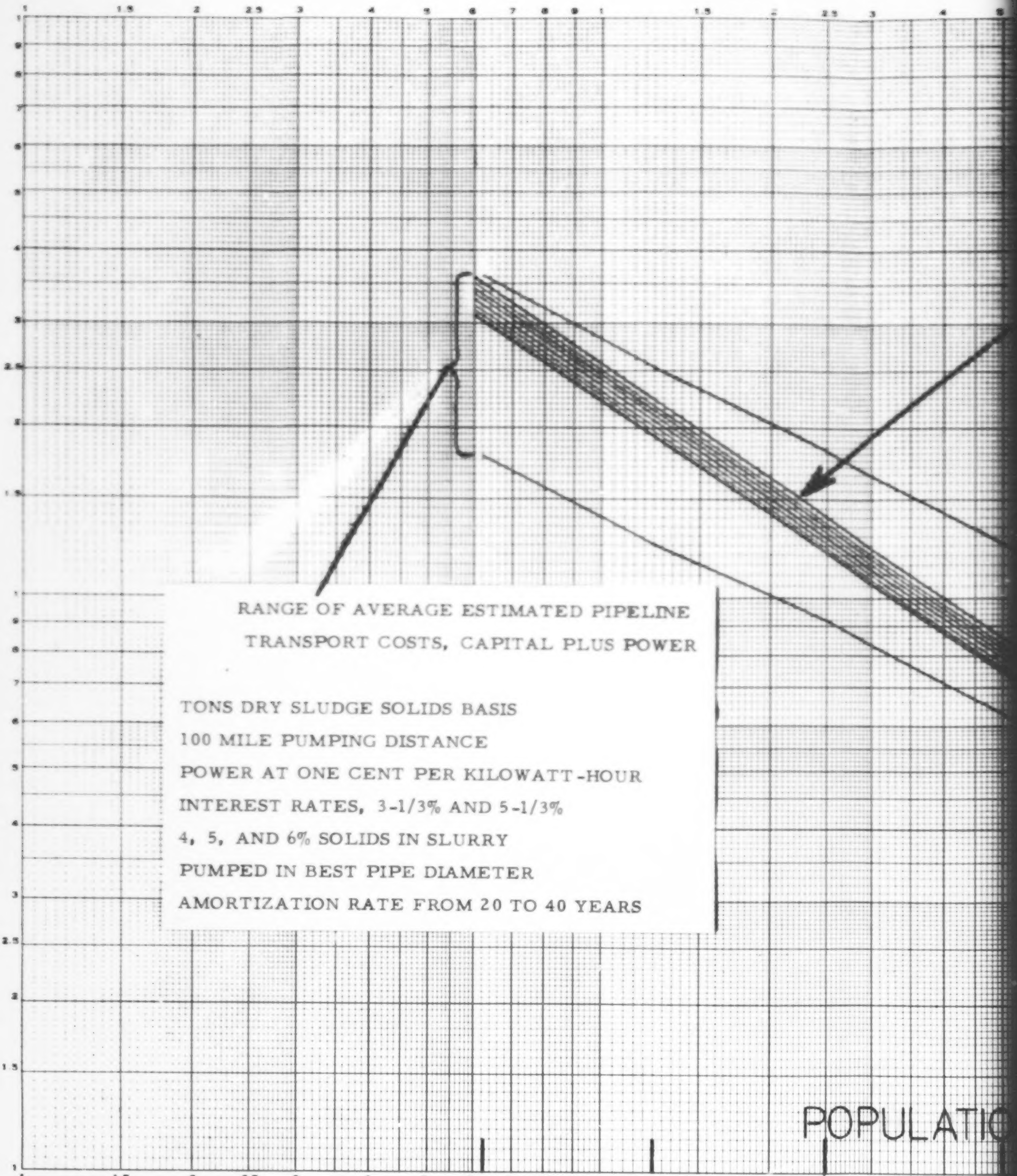
INTEREST RATE, 3-1/3%

MINIMUM SOLIDS IN SLURRY, 4%

PIPE LIFE RELATED TO ONE PIPE SIZE OVER OPTIMUM SIZE FOR EACH POPULATION, 20 TO 70 YEARS

DOLLARS/DRY TON
40
30
20
10
6
4
3
2
1
YEARS
35
36
48
53
62
70
LATION (MILLIONS)
25
.5
1
2
4
8

B



RANGE OF AVERAGE ESTIMATED PIPELINE TRANSPORT COSTS, CAPITAL PLUS POWER

TONS DRY SLUDGE SOLIDS BASIS

100 MILE PUMPING DISTANCE

POWER AT ONE CENT PER KILOWATT-HOUR

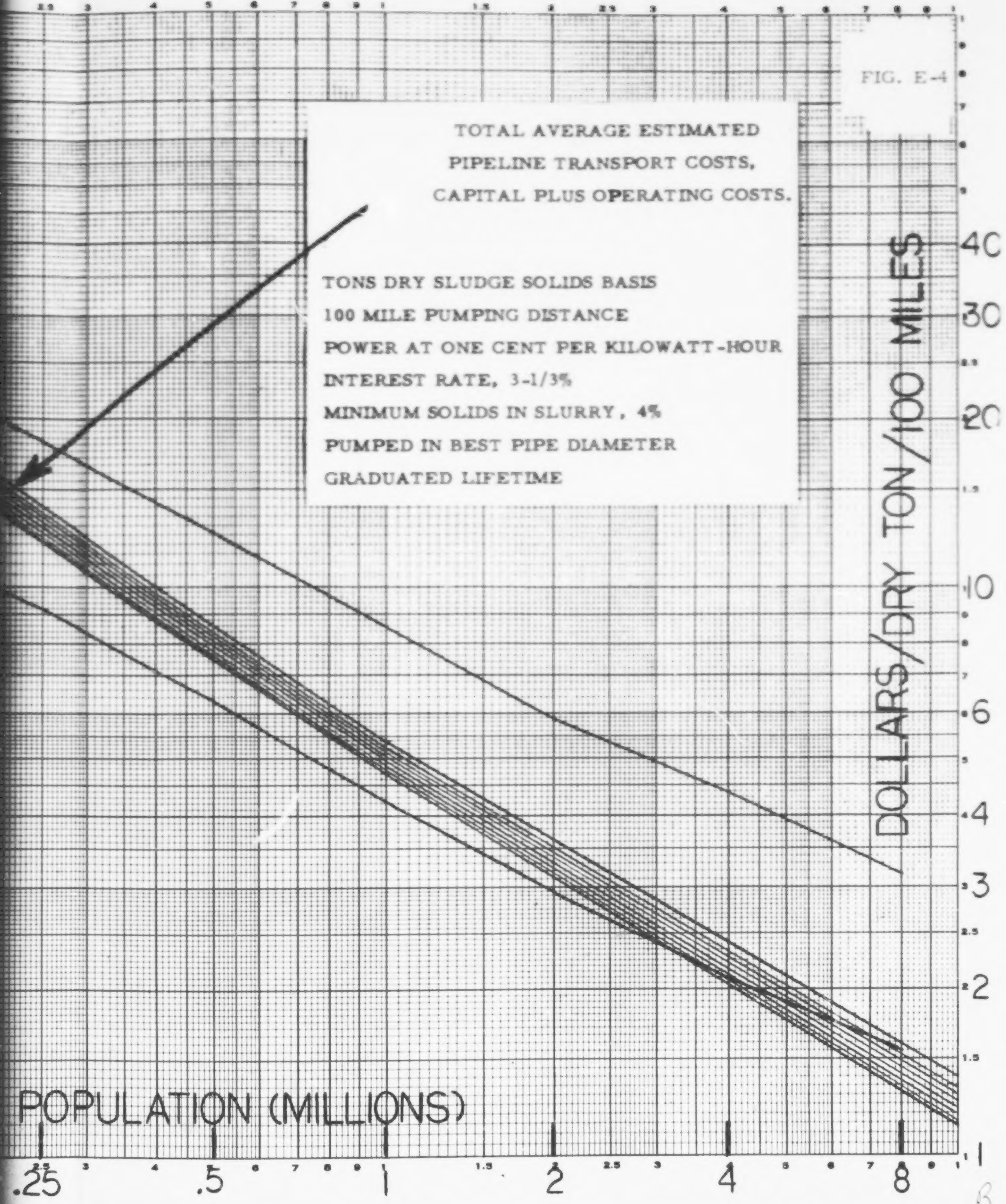
INTEREST RATES, 3-1/3% AND 5-1/3%

4, 5, AND 6% SOLIDS IN SLURRY

PUMPED IN BEST PIPE DIAMETER

AMORTIZATION RATE FROM 20 TO 40 YEARS

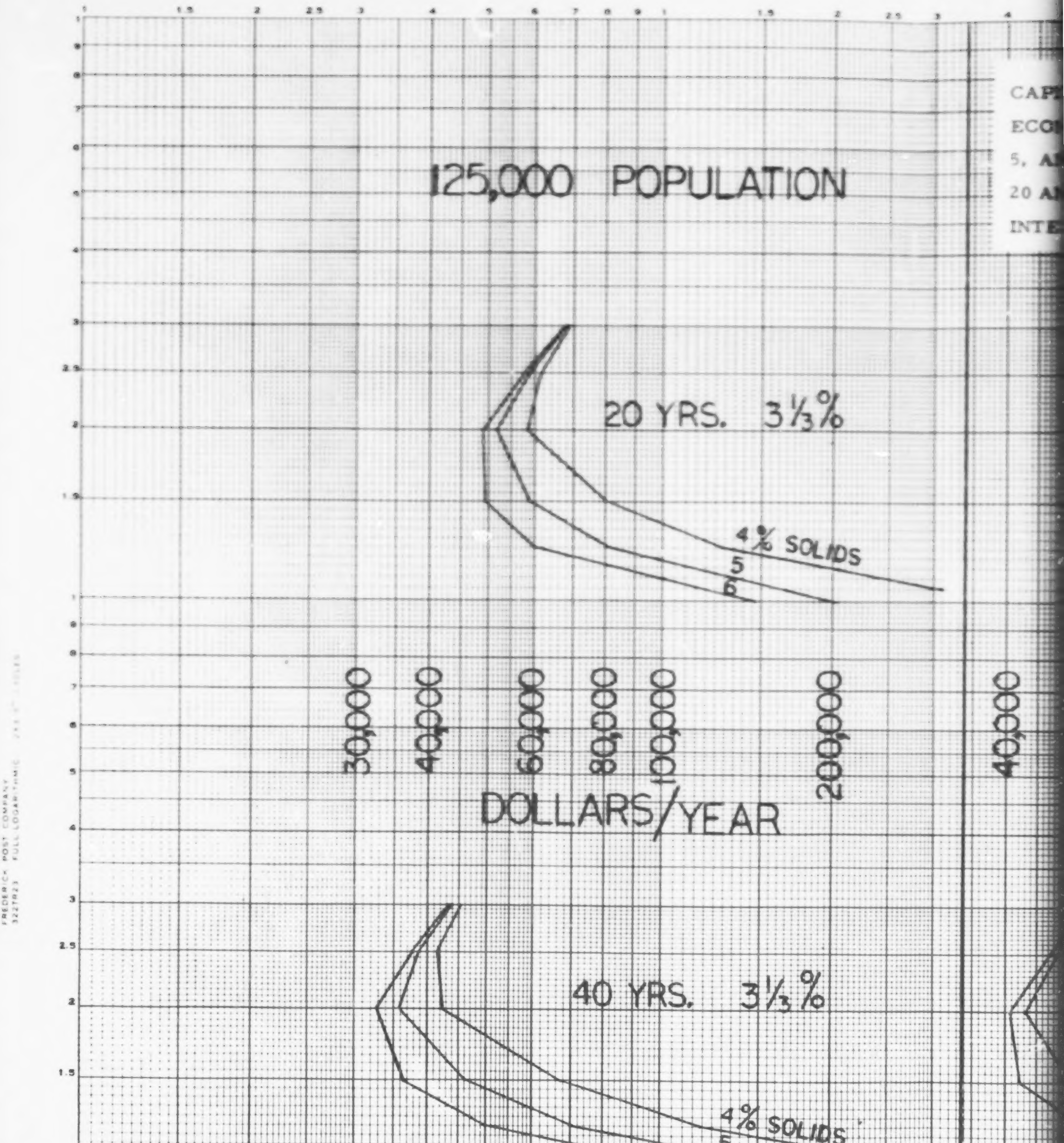
FIG. E-4



TOTAL AVERAGE ESTIMATED PIPELINE TRANSPORT COSTS, CAPITAL PLUS OPERATING COSTS.

TONS DRY SLUDGE SOLIDS BASIS
100 MILE PUMPING DISTANCE
POWER AT ONE CENT PER KILOWATT-HOUR
INTEREST RATE, 3-1/3%
MINIMUM SOLIDS IN SLURRY, 4%
PUMPED IN BEST PIPE DIAMETER
GRADUATED LIFETIME

B

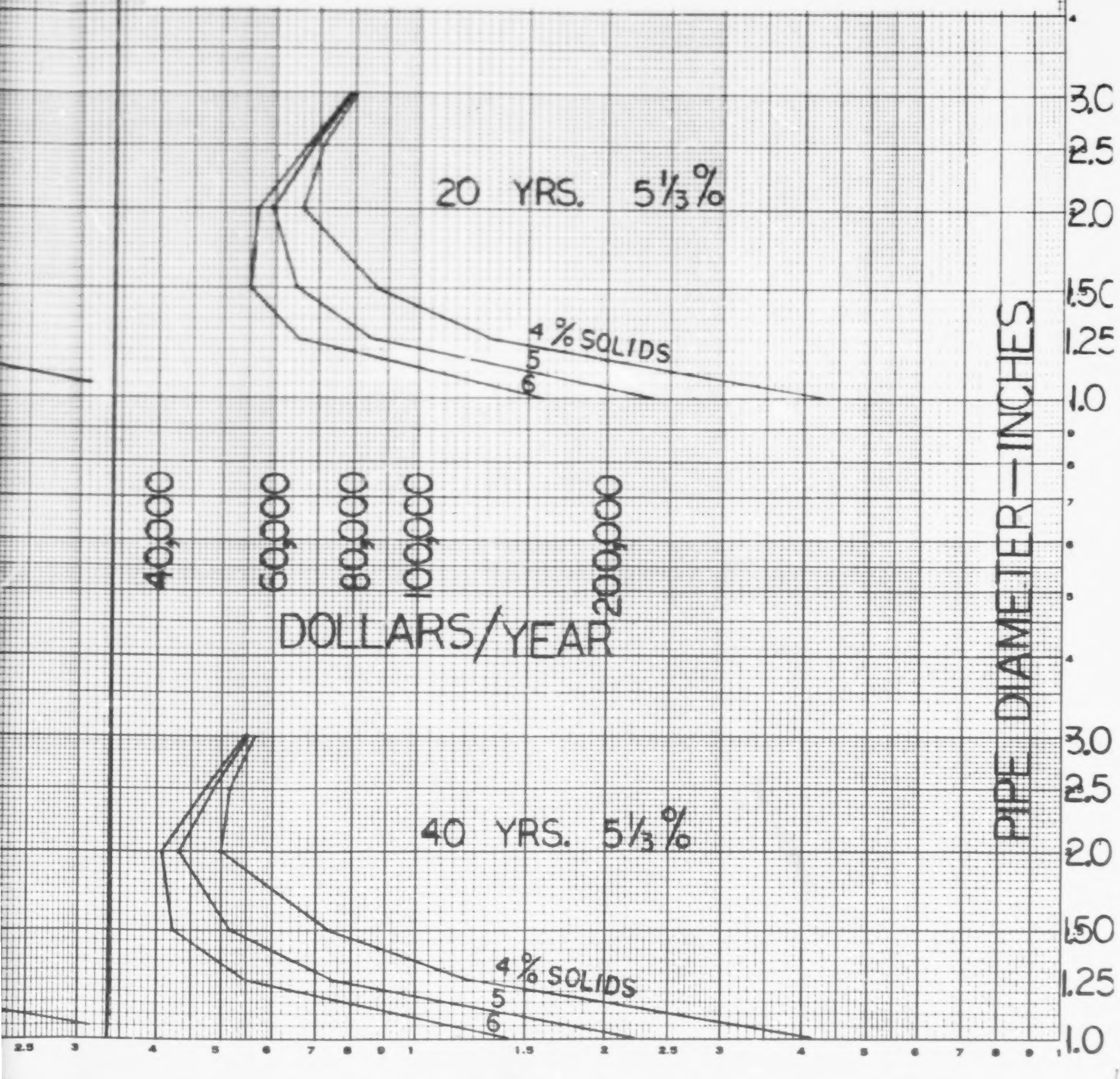


CAP
ECO
5, A
20 A
INTE

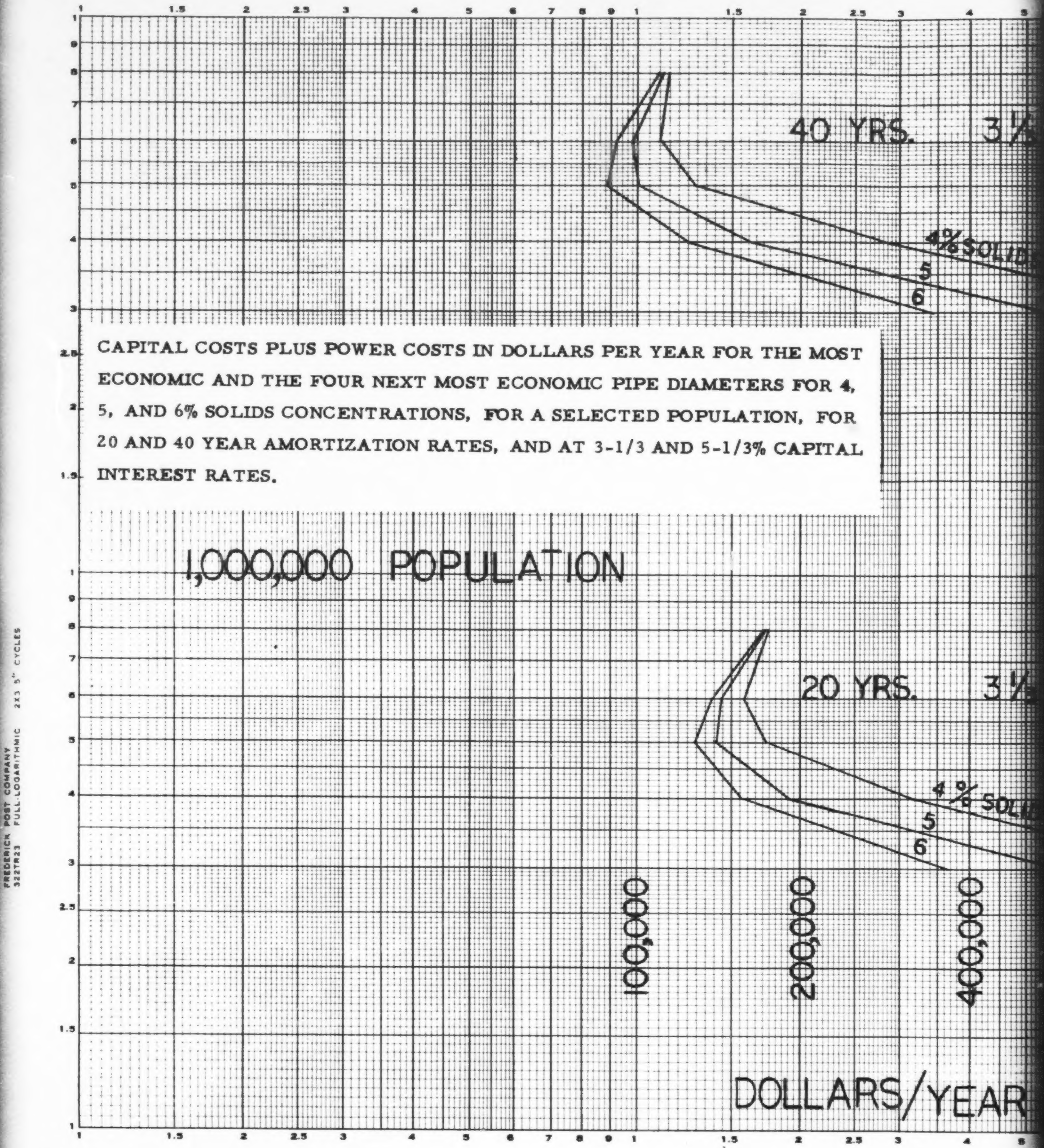
A

FIG. E-5

CAPITAL COSTS PLUS POWER COSTS IN DOLLARS PER YEAR FOR THE MOST ECONOMIC AND THE FOUR NEXT MOST ECONOMIC PIPE DIAMETERS FOR 4, 5, AND 6% SOLIDS CONCENTRATIONS, FOR A SELECTED POPULATION, FOR 20 AND 40 YEAR AMORTIZATION RATES, AND AT 3-1/3 AND 5-1/3% CAPITAL INTEREST RATES.



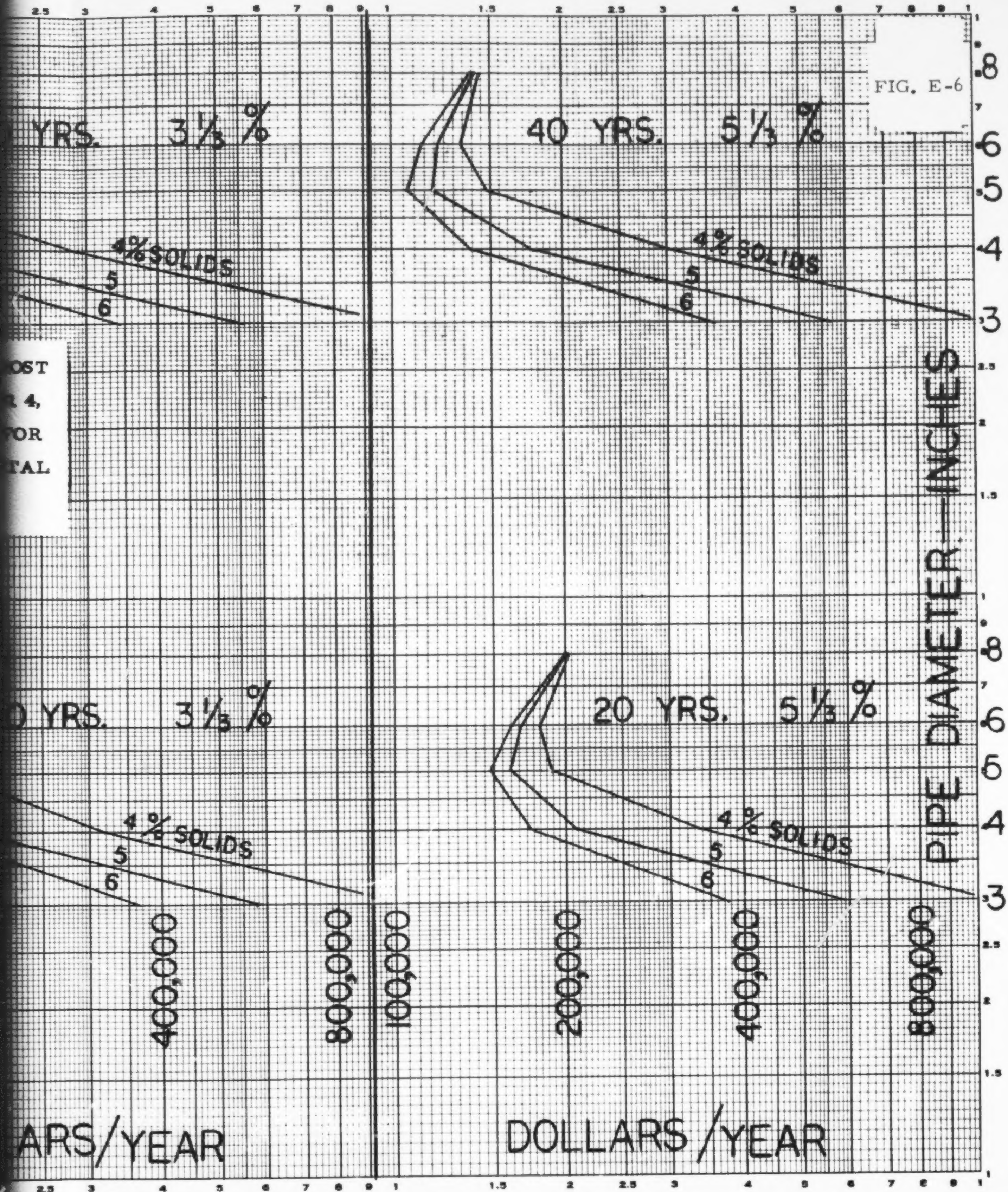
B



CAPITAL COSTS PLUS POWER COSTS IN DOLLARS PER YEAR FOR THE MOST ECONOMIC AND THE FOUR NEXT MOST ECONOMIC PIPE DIAMETERS FOR 4, 5, AND 6% SOLIDS CONCENTRATIONS, FOR A SELECTED POPULATION, FOR 20 AND 40 YEAR AMORTIZATION RATES, AND AT 3-1/3 AND 5-1/3% CAPITAL INTEREST RATES.

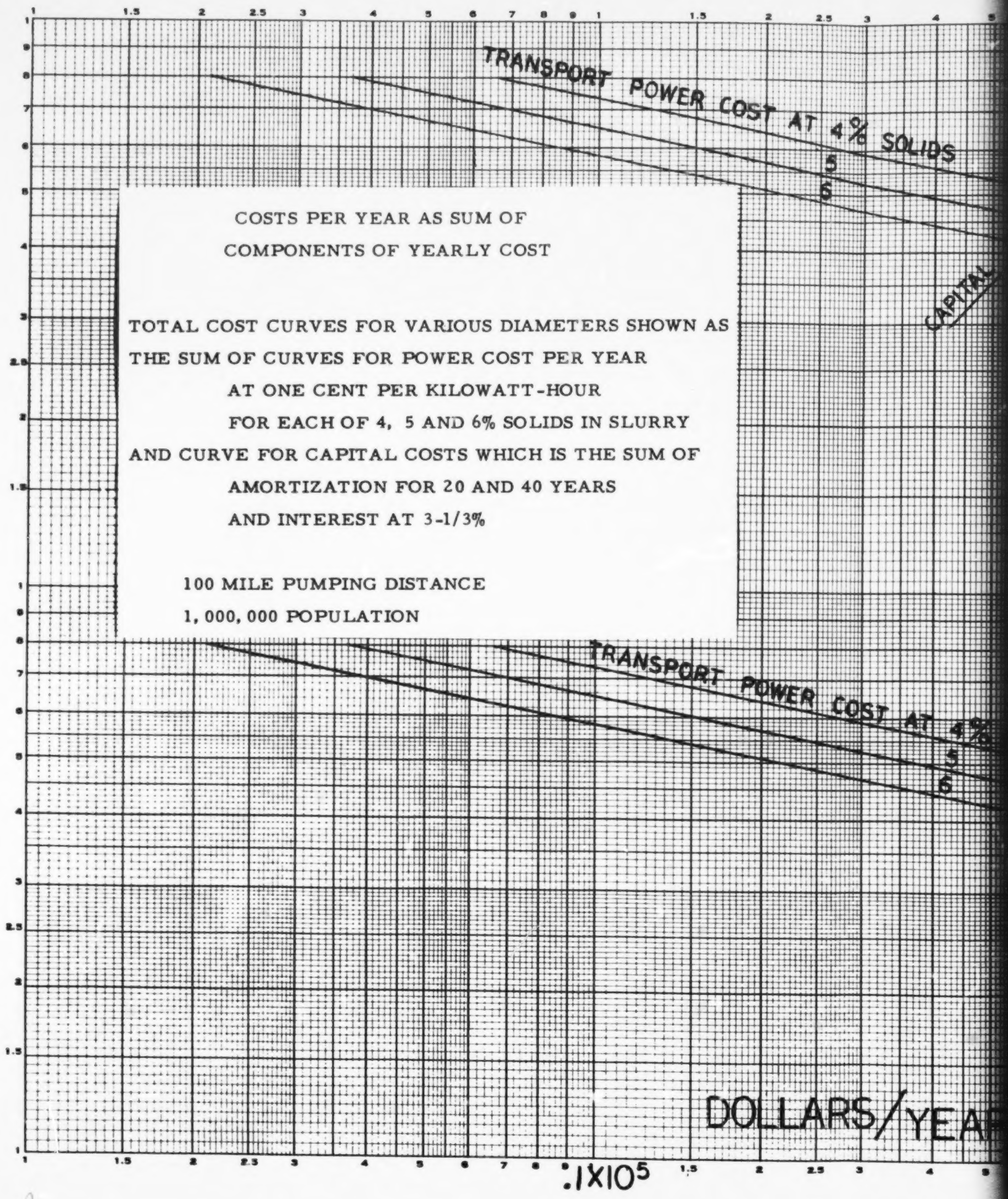
A

FIG. E-6



YRS. 3⅓ %
4% SOLIDS
5
6
OST
R 4,
OR
TAL
O YRS. 3⅓ %
4 % SOLIDS
5
6
400,000
800,000
ARS/YEAR
40 YRS. 5⅓ %
4% SOLIDS
5
6
20 YRS. 5⅓ %
4 % SOLIDS
5
6
100,000
200,000
400,000
800,000
DOLLARS/YEAR
PIPE DIAMETER—INCHES
8
6
5
4
3

B



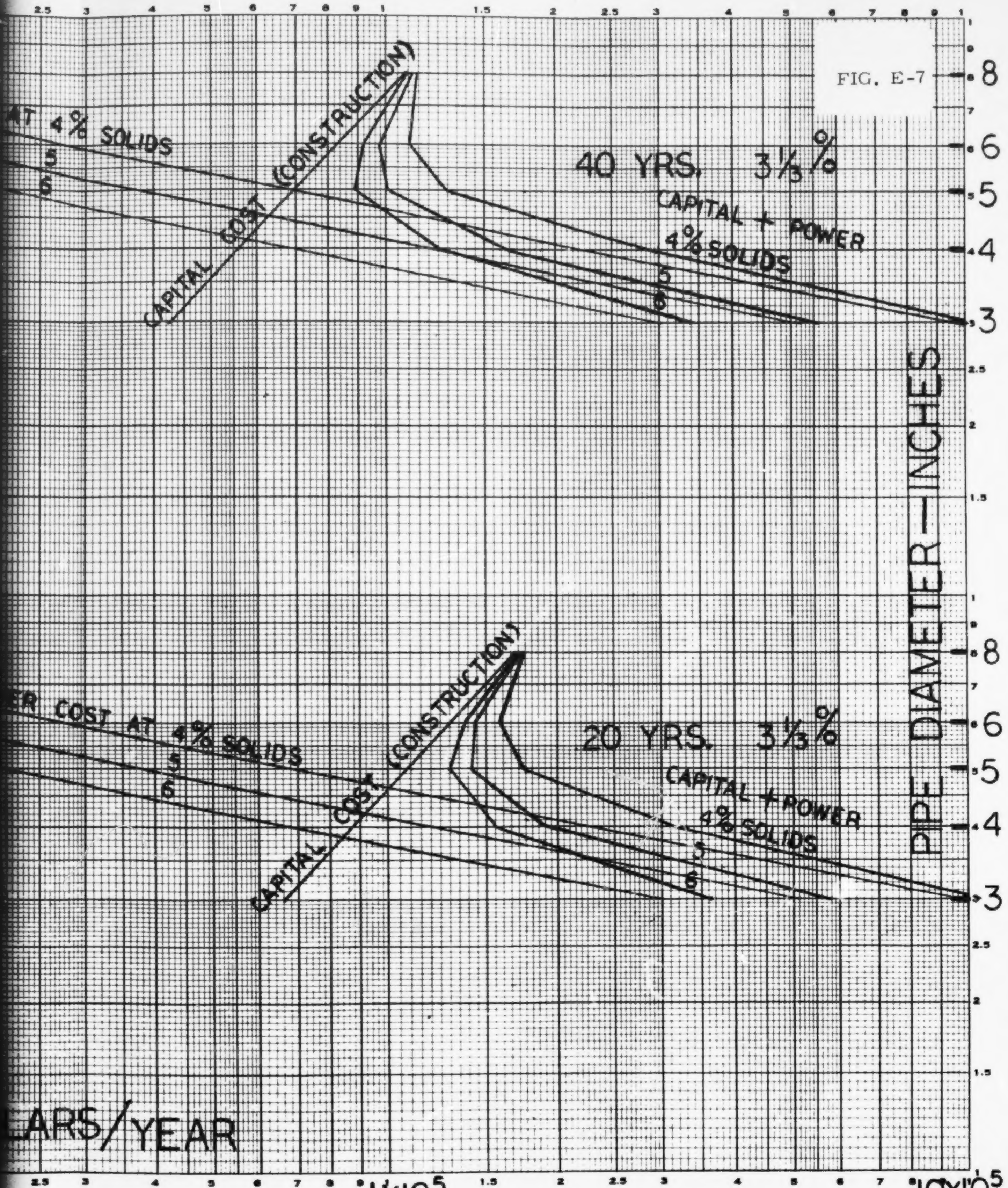
COSTS PER YEAR AS SUM OF
COMPONENTS OF YEARLY COST

TOTAL COST CURVES FOR VARIOUS DIAMETERS SHOWN AS
THE SUM OF CURVES FOR POWER COST PER YEAR
AT ONE CENT PER KILOWATT-HOUR
FOR EACH OF 4, 5 AND 6% SOLIDS IN SLURRY
AND CURVE FOR CAPITAL COSTS WHICH IS THE SUM OF
AMORTIZATION FOR 20 AND 40 YEARS
AND INTEREST AT 3-1/3%

100 MILE PUMPING DISTANCE
1,000,000 POPULATION

A

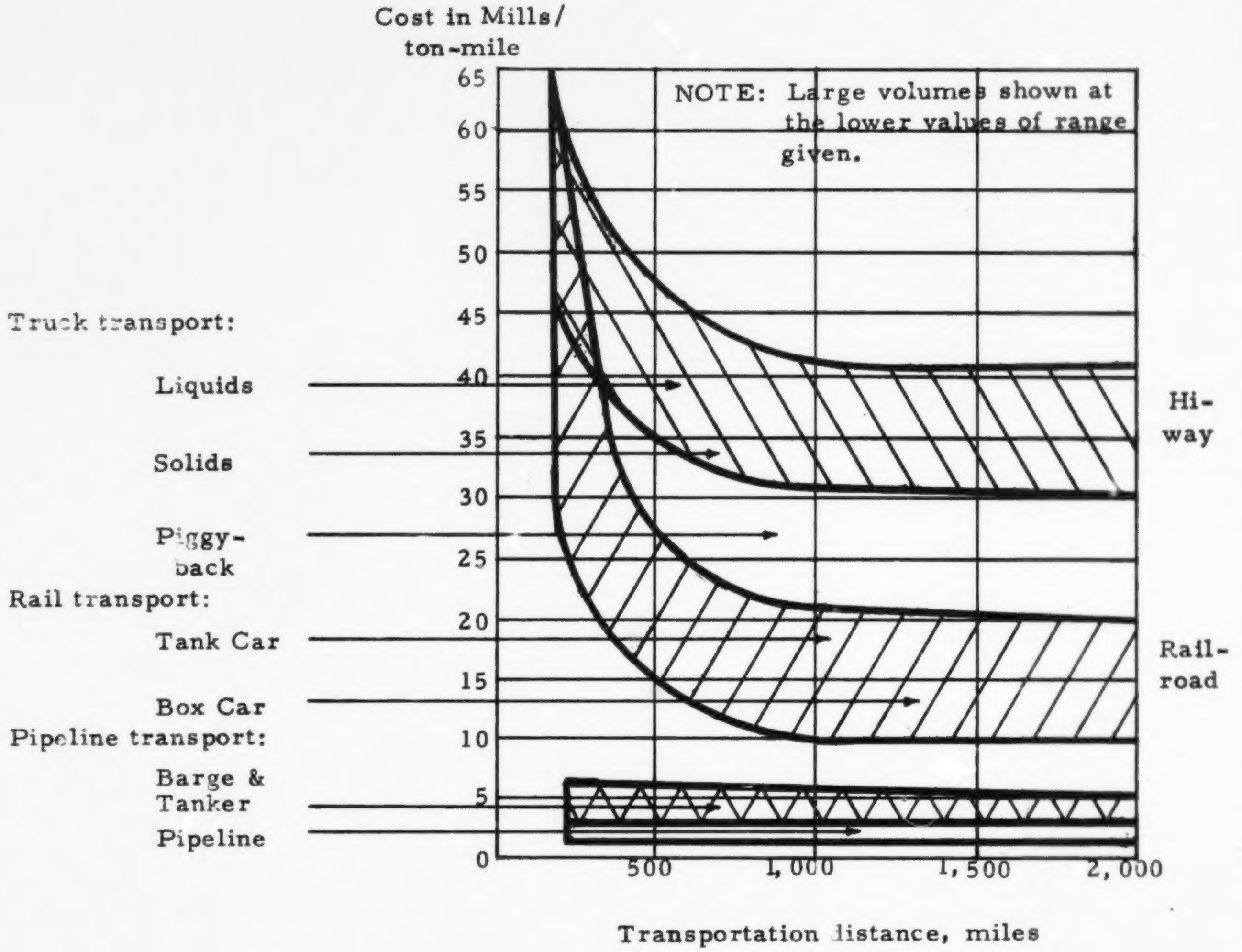
FIG. E-7


AT 4% SOLIDS
5
6
CAPITAL COST (CONSTRUCTION)
40 YRS. 3⅓%
CAPITAL + POWER
4% SOLIDS
5
6
ER COST AT 4% SOLIDS
5
6
CAPITAL COST (CONSTRUCTION)
20 YRS. 3⅓%
CAPITAL + POWER
4% SOLIDS
5
6
PIPE DIAMETER — INCHES
8
6
5
4
3
8
6
5
4
3
LARS/YEAR
2.5
3
4
5
6
7
8
9
1
1.5
2
2.5
3
4
5
6
7
8
9
1
1X10^5
10X10^5

B

FIG. E-8

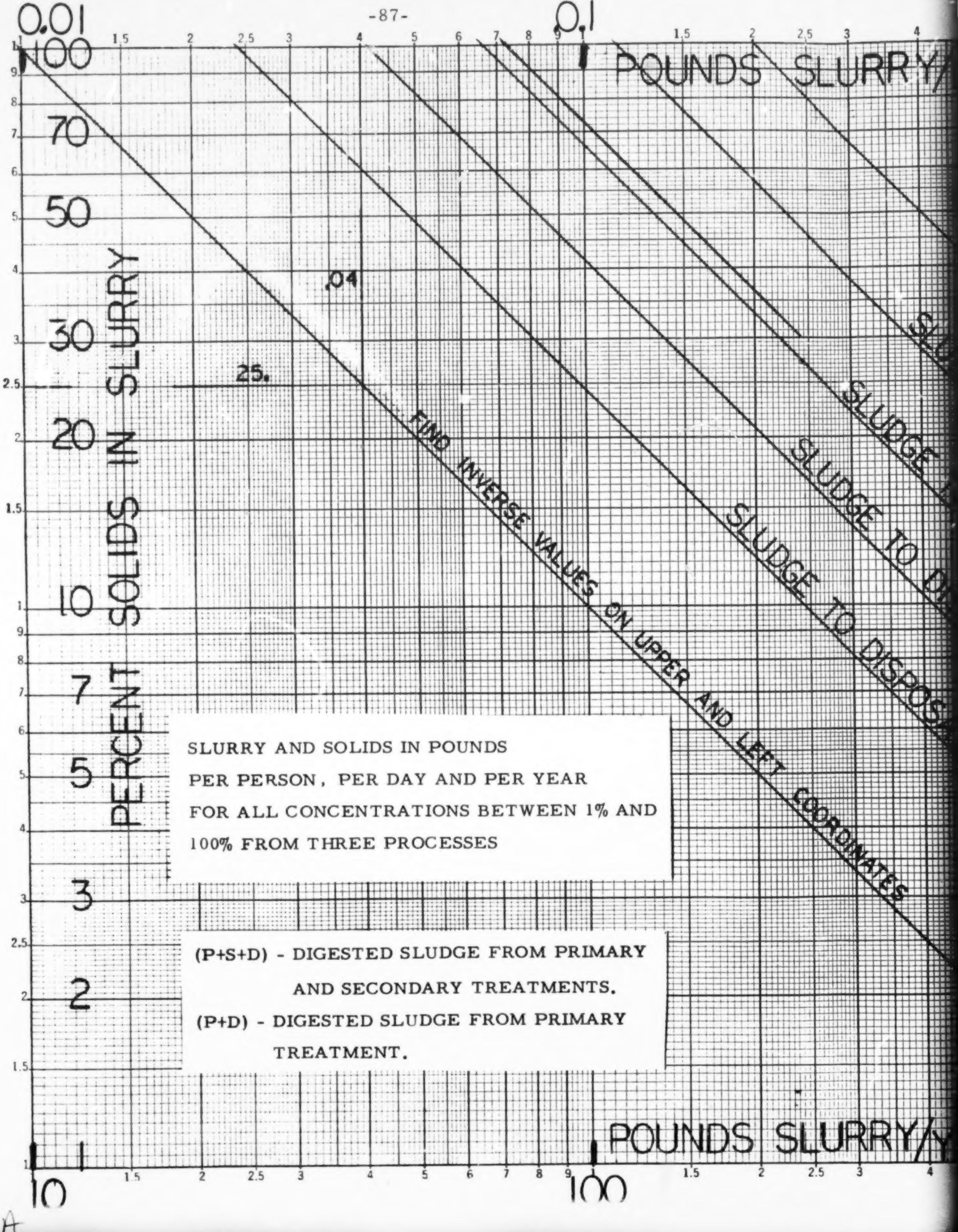
Bulk Transportation Costs



NOTE: Large volumes shown at the lower values of range given.

APPENDIX "F"

Digested Sludge Production



SLURRY AND SOLIDS IN POUNDS
PER PERSON, PER DAY AND PER YEAR
FOR ALL CONCENTRATIONS BETWEEN 1% AND
100% FROM THREE PROCESSES

(P+S+D) - DIGESTED SLUDGE FROM PRIMARY AND SECONDARY TREATMENTS.

(P+D) - DIGESTED SLUDGE FROM PRIMARY TREATMENT.

K+E LOGARITHMIC 358-112L
KEUFFEL & ESSER CO. MADE IN U.S.A.
2 X 3 CYCLES

A

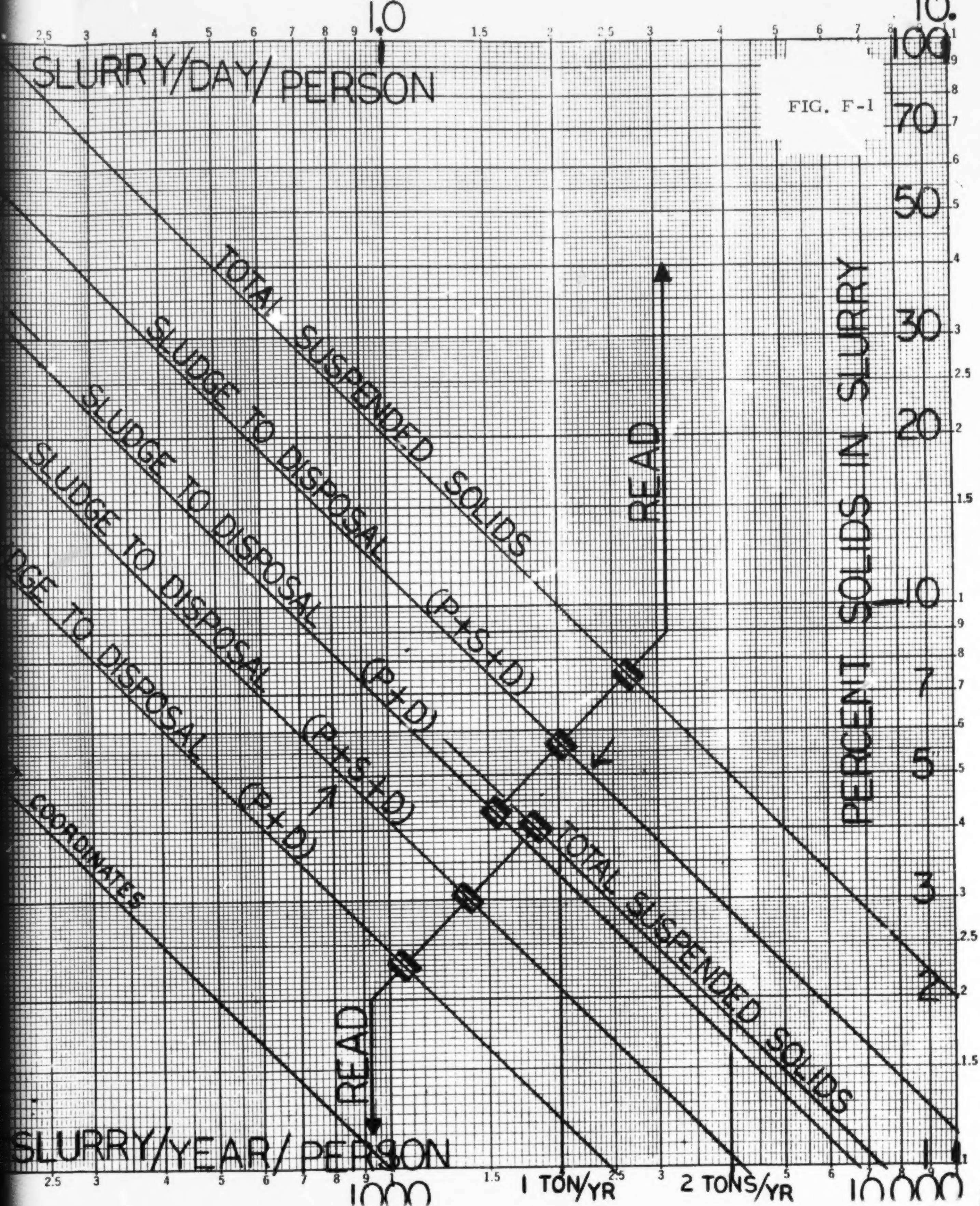
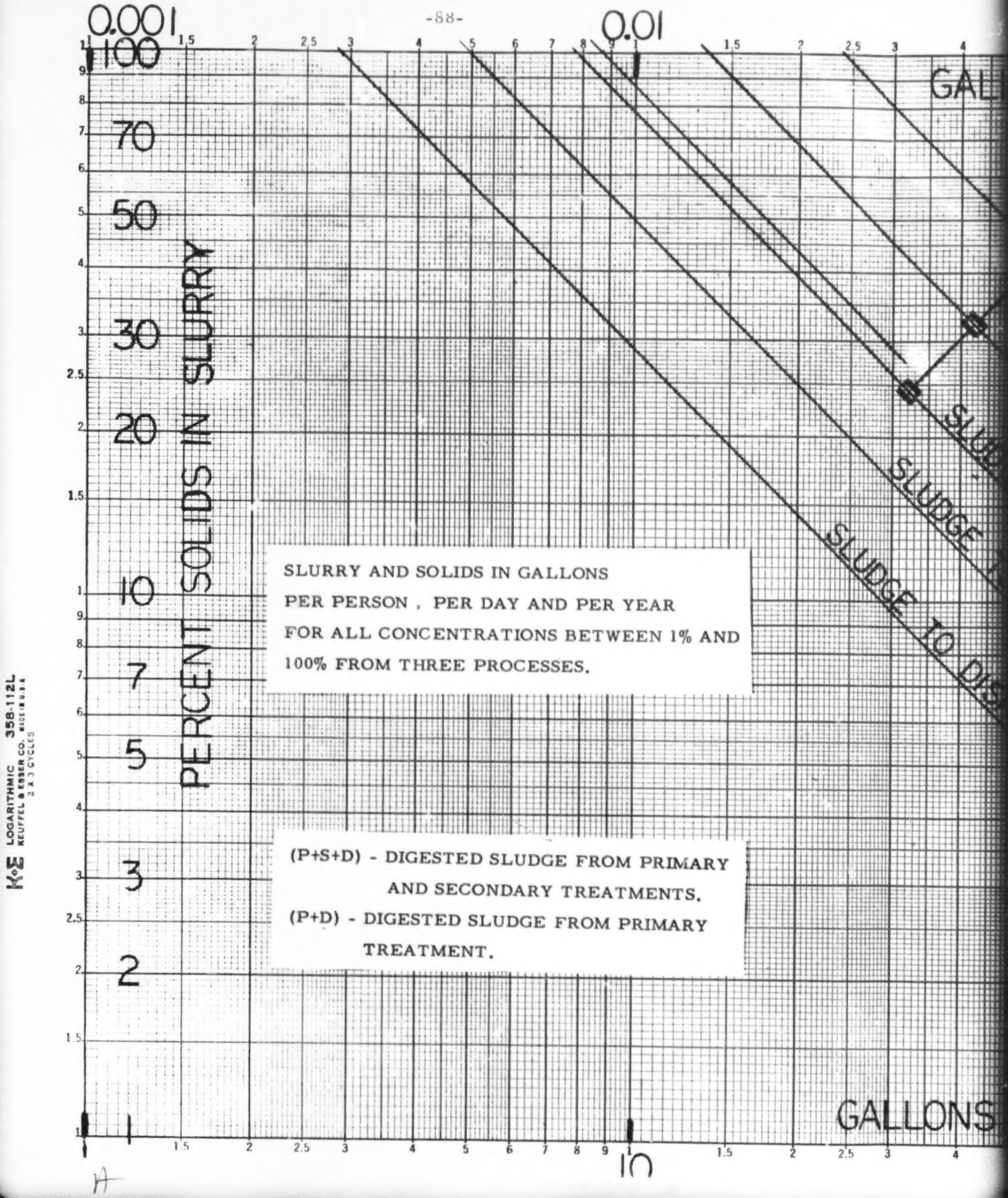


FIG. F-1

1.0
10.
2.5
3
4
5
6
7
8
9
1.5
2
2.5
3
4
5
6
7
8
SLURRY/DAY/PERSON
100
70
50
30
20
10
7
5
3
2
1
PERCENT SOLIDS IN SLURRY
TOTAL SUSPENDED SOLIDS
SLUDGE TO DISPOSAL (P+S+D)
SLUDGE TO DISPOSAL (P+D)
SLUDGE TO DISPOSAL (P+S+D)
DGE TO DISPOSAL (P+D)
COORDINATES
TOTAL SUSPENDED SOLIDS
READ
READ
SLURRY/YEAR/PERSON
1000
1 TON/YR
2 TONS/YR
10000

B



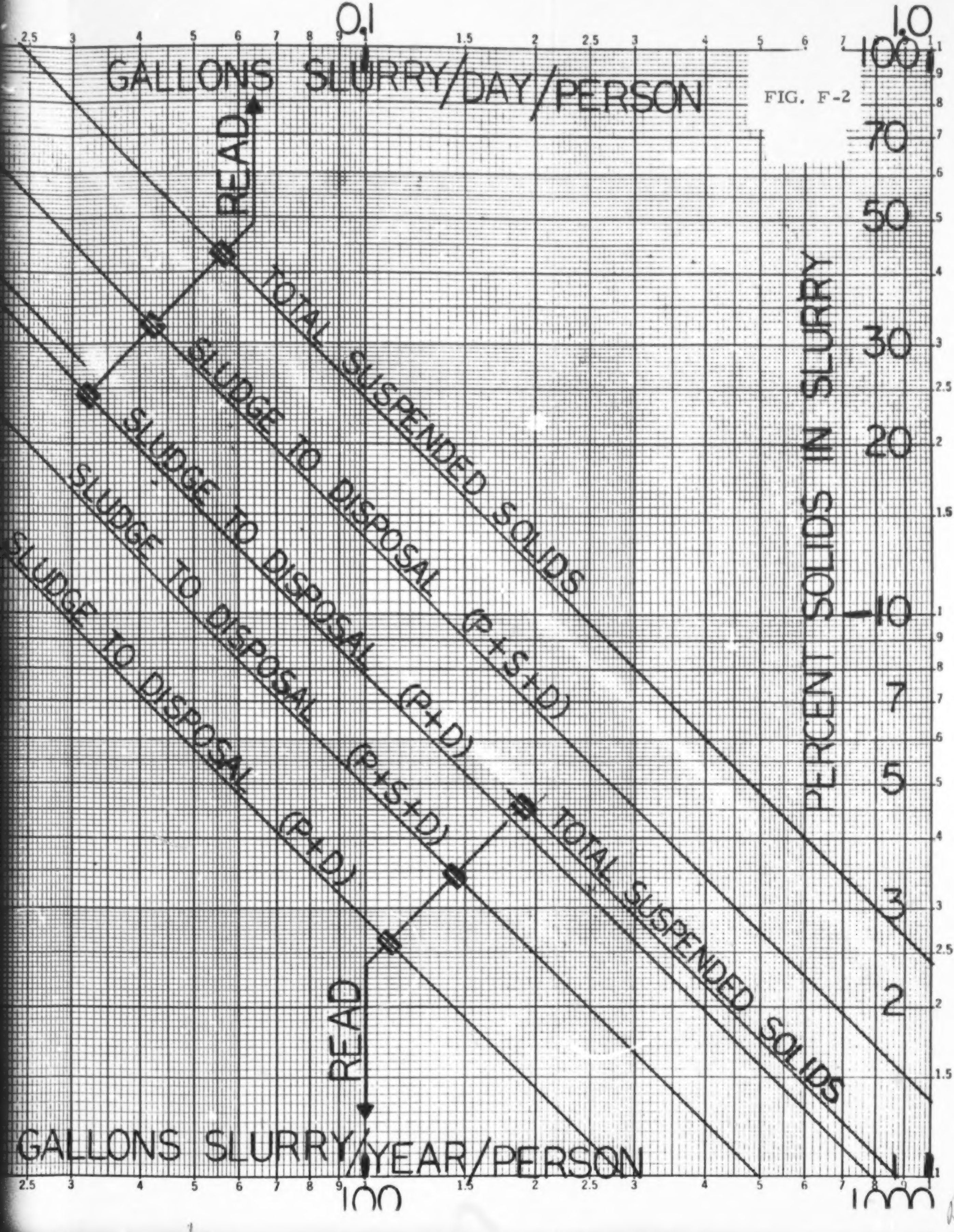
SLURRY AND SOLIDS IN GALLONS PER PERSON , PER DAY AND PER YEAR FOR ALL CONCENTRATIONS BETWEEN 1% AND 100% FROM THREE PROCESSES.

(P+S+D) - DIGESTED SLUDGE FROM PRIMARY AND SECONDARY TREATMENTS.

(P+D) - DIGESTED SLUDGE FROM PRIMARY TREATMENT.

A

FIG. F-2


0.1
1.0
GALLONS SLURRY/DAY/PERSON
READ
TOTAL SUSPENDED SOLIDS
SLUDGE TO DISPOSAL (P+S+D)
SLUDGE TO DISPOSAL (P+D)
SLUDGE TO DISPOSAL (P+S+D)
SLUDGE TO DISPOSAL (P+D)
TOTAL SUSPENDED SOLIDS
READ
PERCENT SOLIDS IN SLURRY
100
70
50
30
20
10
7
5
3
2
1
GALLONS SLURRY/YEAR/PERSON
100
1000

B

VI. REFERENCES

1. Economic Transport and Disposal of Sludge Slurries, Nov. 15, 1965, Contract No. PH 86-65-21 Final Report by Rand Development Corporation, Cleveland, Ohio.

2. Alves, G. E., Boucher, D. F., and Pigford, R. L., Pipeline Design for Non-Newtonian, Chemical Eng. Prog., 48, No. 8, p. 385-393 (1952).

3. Colorado School of Mines Research Foundation, Inc., Golden, Colorado, "The Transportation of Solids in Steel Pipelines", 1963, $3.50. Sponsored by the Subcommittee on Line Pipe Research of the Tech. Committee on Pipe of American Iron and Steel Inst., N. Y., N. Y.

4. Condolios, Elie, and Chapus, Edmund E., Sogreak Co. I. Chem. Eng., June 24, 1963, p. 93-98, "Transporting Solid Materials in Pipelines"; II, Chem. Eng., July 8, 1963, p. 131-138, "Designing Solids-Handling Pipelines"; III. Chem. Eng. July 22, 1963, p. 145-150, "Operating Solids Pipelines".

5. Durand, R. and Condolios, The Hydraulic Transport of Coal and Solid Material in Pipes. Proc. Colloq. on Hydraulic Transportation, London, (Nov. 1952).

6. Ellis, H.S., Redberger, P.J., and Bolt, L.H. Transporting Solids by Pipe Line. Slurries Basic Principles and Power Requirements, Ind. & Eng. Chem. Vol. 55, No. 8, Aug. 1963, p. 18-26.

7. Gregory, W.B., Pumping Clay Slurry Through a Four-Inch Pipe, Mech. Eng. Vol. 39, p. 609 (1927).

8. Harleman, Donald R.F., Assoc. Prof. of Hydraulics, M.I.T., Flow Resistance in Pipes and Fittings (A Fundamental Discussion of an item of Basic Interest) Water and Sewage Works, Nov. 1959, p. 465-474.

9. Holland, F. Anthony, Scale-Up of Fluid Flow Systems, Chem. Eng. Dec. 24, 1962, p. 71, Sept. 17, 1962, p. 184.

10. Hubbell, George E., "Dearborn Sewage Sludge Pumped Through Long Pipe Lines", p. 343, Engineering News Record, Vol. III, 1933.

11. Hydraulic Institute, Correlation of Data Derived from Two Surveys on Velocities and Friction Losses Involved in Pumping of Fluid-Solid Mixtures, Hydraulic Institute, N.Y. - Nov. 1959.

12. Kemler, Emory, "Study of the Data on the Flow of Fluids in Pipes", Trans. ASME Vol. 55, Hyd. 55-2, Page 497, 1933.

13. Kharabanda, O.P., D. Ch. E. AMI Chem. E., Nomograms for Chemical Engineers, Heywood & Co., Ltd., London, 1958, p. 178-9.

14. Metzner, A.B., Chem. Eng. Prog. 50, 27 P. 243, 1954.

15. Metzner, A. B., Reed, J.C., Flow of Non-Newtonian Fluids - Correlation of Laminar, Transition and Turbulent Flow Regions, J. Am. Inst. of Chem. Engrs., Vol. 1, No. 4, Dec. 1950, pp. 434-440.

16. Moody, L. F., Friction Factors for Pipe Flow, Transactions of the Am. Soc. of Mechanical Engineers, Nov. 1944, 66, 671-684.

17. Narver, D. L. and Graham, E.H., Jr., Two Long Ocean Outfalls Constructed, Civil Eng. 28, 1 Jan. 1958.

18. Newitt, D.M., Richardson, J.F., Abbott, M., Turtle, R.B., Hydraulic Conveying of Solids in Horizontal Pipes, Trans. Inst. Chem. Eng., V. 33, p. 93 (1955).

19. Potts, W.E., Brinkerhoff, R. (Lever Bros. Co., Chapman, F.S., and Holland, F.A., Pipelines for Non-Newtonian Liquids)Chem. Eng. p. 185-190, March 15, 1965.

20. Ramalho, R.S., Tiller, F.M., Berry, V.J., Jr., New Friction-Factor Chart for Pipe Flow, Chem. Engrg., July 20, 1964, p. 153-154.

21. Rankin, L.S., "Flow of Non-Newtonian Fluids in Rectangular Pipes", Thesis, M. Ch. Eng. Univ. of Delaware, Newark, Delaware (June, 1955).

22. Reynolds, Osborn, An Experimental Investigation of the Circumstances Which Determine Whether Motion of Water Shall be Direct or Sinous and of the Law of Resistance in Parallel Channels, Royal Society, London, Phil. Trans. Vol. 174, Pt. 3, p. 935.

23. Rothfus, Archer, Klimas, and Sikchi, Velocity Ratio vs. Reynolds Number for Smooth Circular Pipes, Am. Inst. Chem. Engrs. J. 3, 208 (1957).

24. Wilhelm, R.H., Wroughton, D.M. and Loeffel, W.L., Flow of Suspensions Through Pipes, Ind. & Eng. Chem., Ind. Ed. Vol. 31, p. 622 (1939).

25. Wirts, J. J., "Pipe Line Transportation and Disposal of Digested Sludge", Sewage and Industrial Wastes, 28, 2, 121 (Feb. 1956).

26. Wirts, J. J., "Sludge Pumping Through Long Force Mains", Water and Sewage Works 95, 10, 345 (1948).

27. Wolfs, J.R., "Factors Affecting Sludge Force Mains", Sewage and Industrial Wastes 22, 1, 1 Jan. 1950.

28. Worster, R.C., The Hydraulic Transport of Solids, Proc. Colloq. on Hydraulic Transportation. London, Nov. 1952.

29. Analysis of Cost Data for Southerly and Easterly Sewage Treatment Plants, Cleveland, Ohio. Private communications and data compiled by Rand Development Corporation.

30. Kershaw, Arnold M., "Developments in Sludge Treatment and Disposal at the Maple Lodge Works, England", Journal Water Pollution Control Federation, Vol. 37, May 1956, p. 674.

31. Metropolitan St. Louis Sewer District Study of Pollution Abatement Report B-1961, Part IV (p. 51-95) Horner & Shifrin, Havens and Emerson, Consulting Engineers.

32. "Examination of Sewage Solids Incineration Costs", Water and Sewage Works, Vol. 104, No. 11, November 1957, p. 479-87.

33. "Modern Sewage Treatment Plants - How Much Do They Cost? A Practical Guide to Estimating Municipal Sewage Treatment Costs", Public Health Service Publication No. 1229.

34. "Costs of Transporting Process Chemicals", Chemical Engineering, Sept. 1962, p. 160.

35. Water Supply and Sewerage, by Steel, 4th Edition, McGraw-Hill publication.

36. Sewage Treatment Plant Design, 1959 Edition, WPCF Manual of Practice No. 8, p. 200.

37. Chou, T., "Resistance of Sewage Sludge to Flow in Pipes", Jour. San. Eng. Div. ASCE 84, SA 5, 1780 (1958).

38. Sirman, John M., "Determination of the Flow Parameters of Sludge " Water and Sewage Works, November 1960, p. 421.

39. Perry's Chemical Engineers' Handbook, Perry, Chilton, and Kirkpatrick, 4th Ed., McGraw-Hill Publ. Sec. 5-29.

40. Alfrey, T., "Mechanical Behavior of High Polymers", Interscience, N.Y. 1948.

41. Alves, G.E., "Non-Newtonian Flow", A Chapter in Fluid and Particle Mechanics Ed. Lapple, C.E., Univ. of Delaware, Newark, Del., 1951, p. 115.

42. Babbitt, H.E., and Caldwell, D.H., "Laminar Flow of Sludges in Pipes with Special Reference to Sewage Sludge", Bull. Univ. of Ill., Urbana, Ill., Vol. 37, No. 12, Nov. 14, 1939, 60 pp., Bull. Series #319.

43. Babbitt, H.E., and Caldwell, D.H., "Flow of Muds, Sludges, and Suspensions in Circular Pipe", Ind. Eng. Chem. 33, 2, 249 (Feb. 1941).

44. Babbitt, H. E., and Caldwell, D.H., "Turbulent Flow of Sludges in Pipes", Bull. Univ. of Ill., Vol. 38, No. 13, Nov. 19, 1940, 44 pp. Bull. Series No. 323

45. Behn, V.C., "Derivation of Flow Equations for Sewage Sludges", (1) Report No. 5, Civil Eng. Dept., Eng. Exp. Sta., Univ. of Delaware, Newark, Delaware, August 1959. (2) Proceedings, ASCE, Vol. 86, No. SA6, (Nov. 1960) p. 59.

46. Behn, V.C., "Flow Equations for Sewage Sludges", Jour., Water Pollution Control Fed., Vol. 32, No. 7, July 1960, p. 728.

47. Behn, V.C., "Experimental Determination of Sludge-Flow Paramete ", J. San. Eng. Div. Proc. ASCE, May 1962, p. 39-54.

48. Boucher, Donald F. and Alves, George E., "Fluid and Particle Mechanics", Sect. 5 of Perry's Chemical Engineering Handbook, 4th Edition, McGraw-Hill, N.Y. 1963.

49. Bowen, R.L., Chem. Eng. June 12, 1961, p. 243, Chem. Eng. July 24, 1961, p. 143.

50. Chou, Tsung-Lien, "Discussion on'Flow of Concentrated Raw Sewage Sludge in Pipes", by Sterling G. Brisbin, Jour. of SED, Vol. 84, No. SA 1, February, 1958.

51. Colorado School of Mines Research Foundation, Inc., Golden, Colorado. "The Transportation of Solids in Steel Pipelines", 1963.

52. Dodge, D. W., "Turbulent Flow of Non-Newtonian Fluids in Smooth Round Tubes", Thesis, Univ. Delaware, Newark, Delaware, June 1958.

53. Dodge, D.W., and Metzner, A.B., "A Theoretical Analysis for Turbulent Flow of Non-Newtonian Fluids is Given", Am. Inst. Chem. Engrs. J , 5, p. 189-204 (1959).

54. Eirich, F.R., "Rheology, Theory & Applications", I - N.Y. Academic Press, 1956, II - N.Y. Academic Press, 1958, III - N.Y. Academic Press, 1960.

55. Fair, G.M. and Geyer, J.C., "Water Supply and Waste Water Disposal", John Wiley & Sons, Inc., N.Y., N.Y., 1954, p. 768.

56. Green, H., "Industrial Rheology and Rheological Structures", Wiley, N.Y., 1949.

57. Hatfield, W.D., "The Viscosity or Pseudo-Plastic Properties of Sewage Sludges", Sewage Works Journal 10, 1, 3 (Jan. 1938), Sewage Works Journal 10, 2, 272 (March, 1938).

58. Holland, F. Anthony, "Another Look at Non-Newtonian Flow", Chem. Eng. Aug. 17, 1964, p. 135-138.

59. Holland, F. Anthony, "Scale-Up of Fluid-Flow Systems", Chem. Eng. Sept. 1 1962, p. 184, and Dec. 24, 1962, p. 71.

60. Imhoff, Karl and Muller, W.S., "Disposal of Sewage and Other Water-Borne Wastes", Butterworth Scientific Publications, London (1956).

61. Jones, Jacob O., "Introduction to Hydraulics and Fluid Mechanics", Harper & Bros. Publ., Chap. VI.

62. Krieger, L.M. and Elrod, H., "Direct Determination of Flow Curves of Non-Newtonian Fluids II, Shearing Rates in the Concentric Cylinder Viscometer", Jour. of Applied Physics, Vol. 24, No. 2, 1953, p. 234-236, Vol. 24, No. 2, 1953, p. 134.

63. Krieger, I.M., and Maron, S.H., "Standardized Treatment of Viscometric Data", Jour. of Applied Physics, Vol. 25, 1954, p. 72.

64. Merkel, W., "Flow Characteristics of Sewage Sludge and other Thick Materials", Physics, 5, 355 (Nov. 1934).

65. Metzner, A.B., "Non-Newtonian Technology", A chapter in: "Advances in Chemical Engineering", Vol. I, Ed. by Drew, T.H. and Hoopes, J.W., Academic Press, Inc., N.Y. 1956.

66. Tatman, D.R., "The Fundamental Rheological Properties of Sewage Sludge", Thesis presented to the Univ. of Delaware at Newark, Del., in 1961, in partial fulfillment of the requirements for the degree of Master of Civil Engineering.

67. Thomas, David G., "Non-Newtonian Suspensions", Part I, Physical Properties & Laminar Transport Characteristics I. & E.C. 55, 11, p. 18-29 (Nov. 1963). Part II, Turbulent Transport Characteristics I. & E.C. 55, 12, p. 27-35 (Dec. 1963).

68. Van Wazer, J.R., Lyons, J.W., Kim, K.Y., and Colwell, R.E., "Viscosity and Flow Measurement", N.Y. Interscience Publishers, Inc., 1963.

69. Weintraub, Murray, "Chemical Engineering Aspects of Fluid Dynamics (Annual Review)", I. & E.C. 56, 4, p. 43-48 (April 1964).

70. Wilkinson, "Non-Newtonian Fluids", Pergamon Press, London, 1960.

71. Worster, R.C., "The Hydraulic Transport of Solids", Proc. Colloq. on Hydraulic Transportation. London, Nov. 1952.

72. Hydraulic Institute Pipe Friction Manual 1961, 3rd Ed., Hydraulic Institute.

73. Einstein, Albert, Ann. Physik 19, 256 (1906), 34, 591 (1911).

74. Study of Strip and Surface Mining in Appalachia, Interim Report to the Appalachian Regional Commission, U.S. Department of the Interior, p. 4.

VII. ACKNOWLEDGEMENTS

We acknowledge with gratitude the generous assistance of many people who have helped in this work. Below is a partial list of those who have assisted us in the past year:

Easterly Pollution Control Center, John J. Wirts, Superintendent

Euclid Sewage Treatment Plant, Edward Schlensker, Superintendent

Mentor Sewage Treatment Plant, Fred Vargo, Superintendent

Munn Septic Tank Cleaning, Jerry Munn

Reclamation & Air Survey, Inc., Jerry K. Kohl, President

Rocky River Sewage Treatment Plant, Ray Rusnak, Superintendent

Southerly Sewage Treatment Plant, Clyde Kirsch, Superintendent

Westerly Sewage Treatment Plant, John O. Barrett, Superintendent, and Leonard Hettinger, Assistant Superintendent

Willoughby-Eastlake Sewage Treatment Plant, George Pforsick, Superintendent

Special thanks to the following individuals for granting permission to use their property:

Captain John Blend, Canton, Ohio

Albert M. Creighton, Waynesberg, Ohio

SIGNED:

Bertram C. Raynes
Bertram C. Raynes

Roger S. Benjamin
Roger S. Benjamin

Harold F. Larson
Harold F. Larson, P.E.

James Surman, Jr.
James Surman, Jr.

Nelson H Wittstock
Nelson H. Wittstock